# Adaptive Optics

AST 401 / 580 Observational Astronomy
Chad Trujillo

# Adaptive Optics:

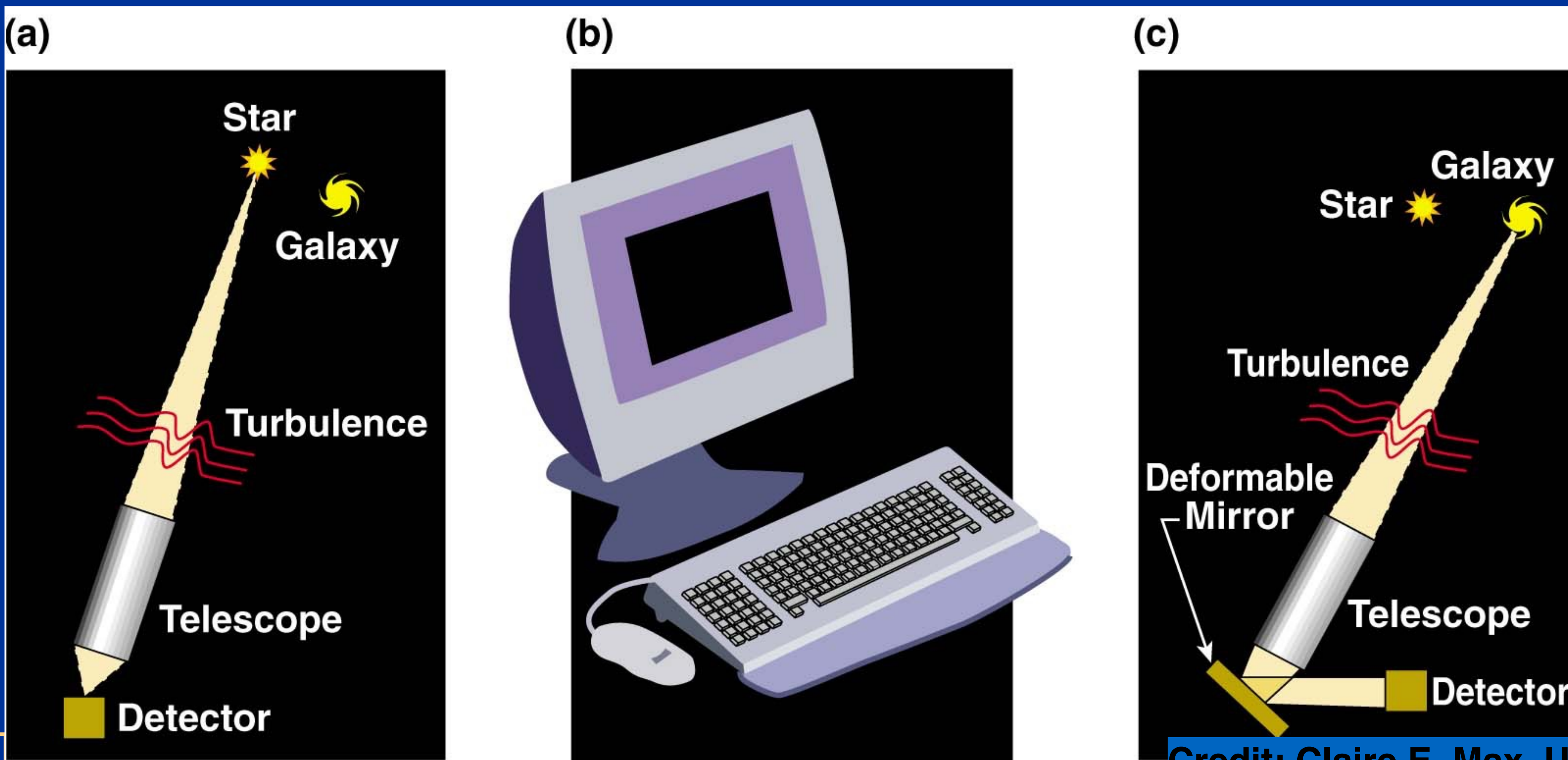
- Corrects for the image degradation due to the atmosphere.
- This is done by combining a fast wavefront sensor(s) with a fast deformable mirror(s).
- It allows large telescopes (> $r_0$ ~ 10 cm) to achieve the diffraction limit.
- For seeing limited telescopes, signal-to-noise goes as the diameter squared ($D^2$).
- For diffraction limited telescopes (i.e. AO), signal-to-noise goes as $D^4$!
- There are many different types of AO available depending on your science case.

# How does adaptive optics help? (cartoon approximation)

*Measure details of blurring from "guide star" near the object you want to observe*

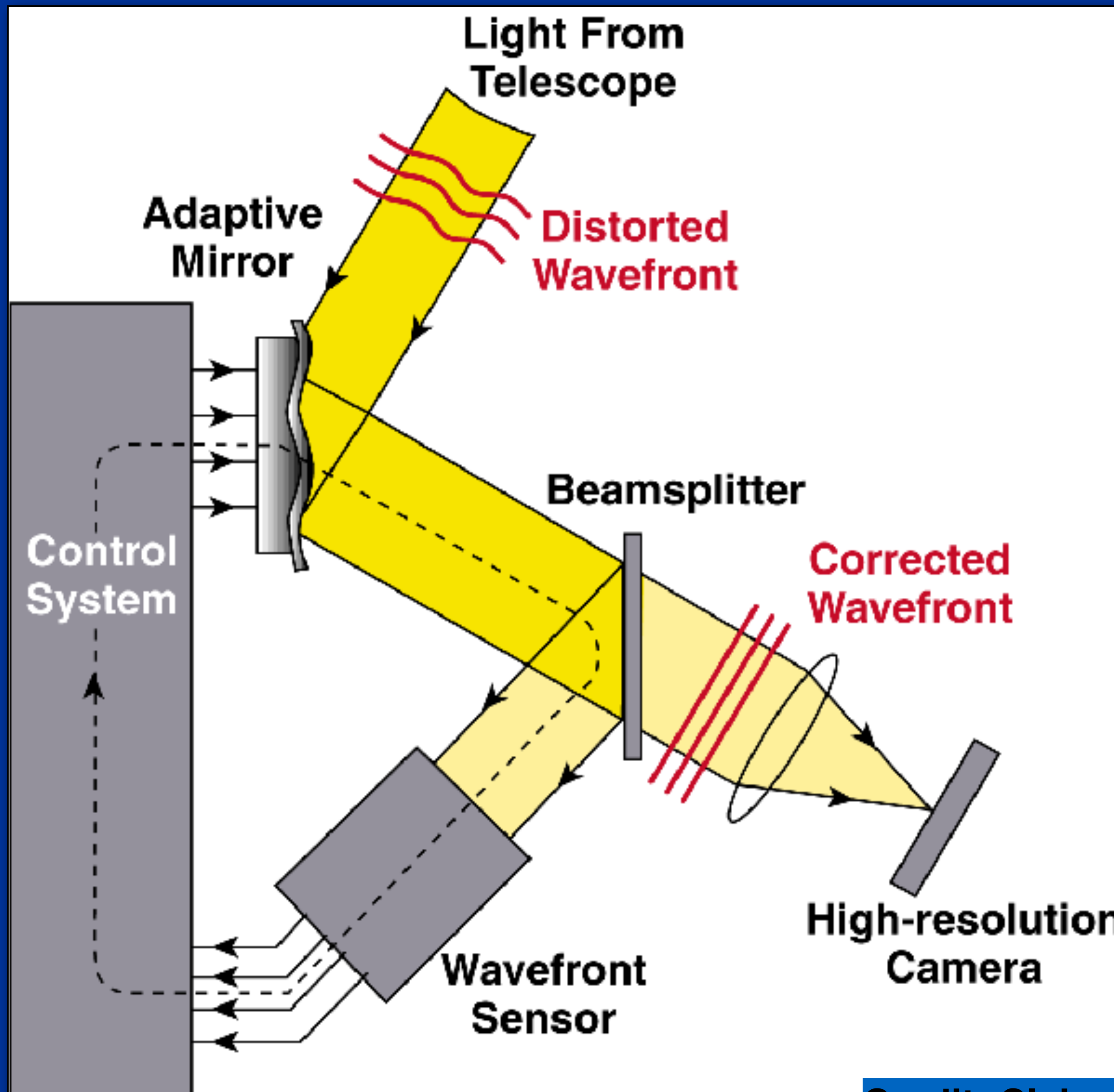
*Calculate (on a computer) the shape to apply to deformable mirror to correct blurring*

*Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed*




Credit: Claire E. Max, UCSC

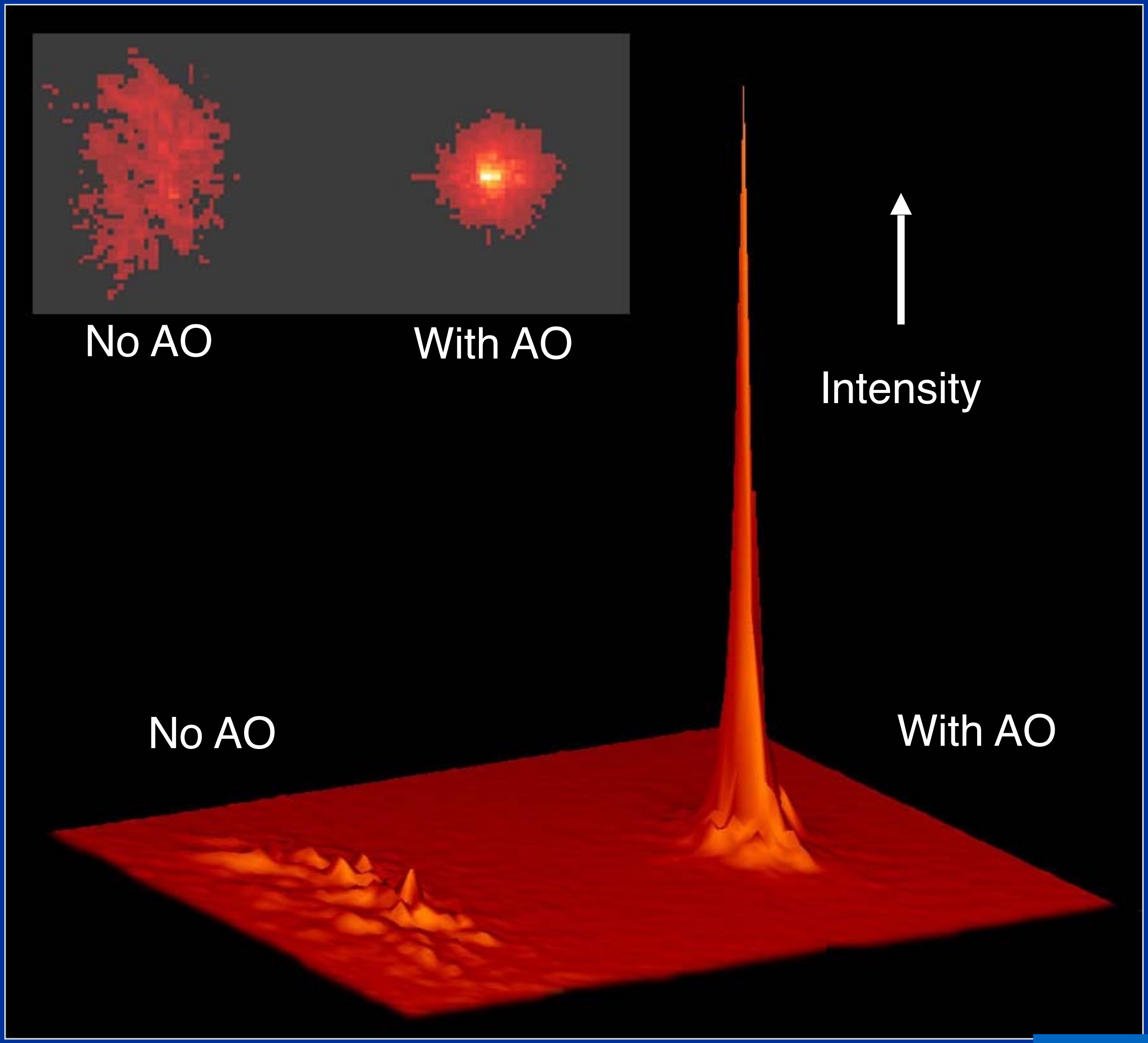
# Schematic of adaptive optics system




Feedback loop: next cycle corrects the (small) errors of the last cycle

Credit: Claire E. Max, UCSC

# *Adaptive optics increases peak intensity of a point source*



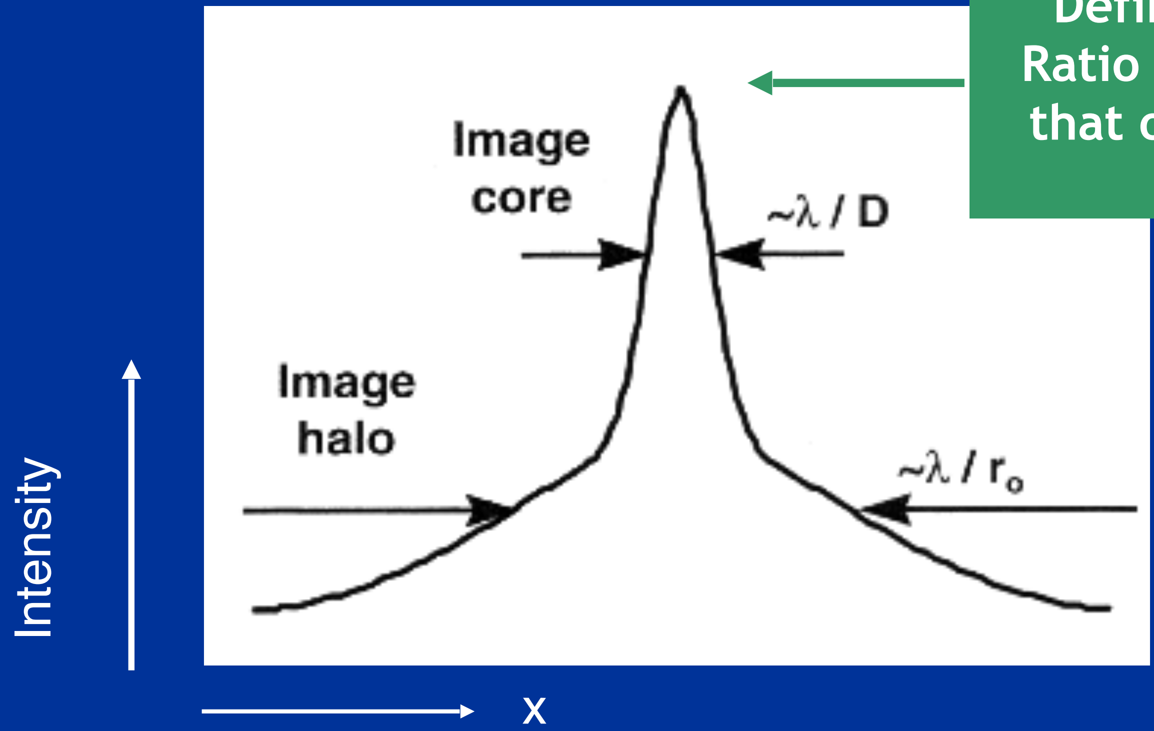

**Lick Observatory**



**Credit: Claire E. Max, UCSC**

## *AO produces point spread functions with a "core" and "halo"*

Definition of "Strehl": Ratio of peak intensity to that of "perfect" optical system




- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ $r_0$)
- Ratio between core and halo varies during night

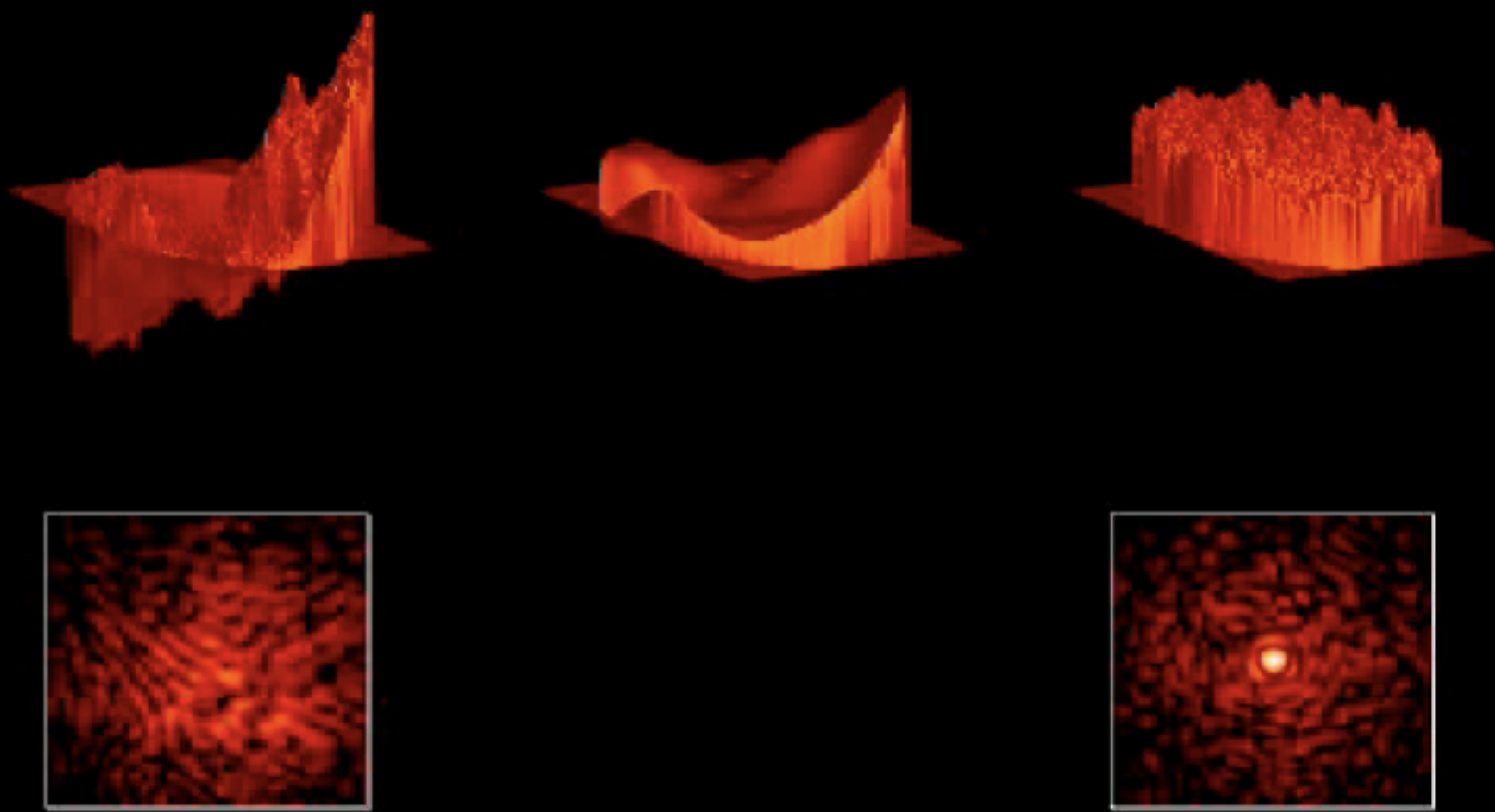


Credit: Claire E. Max, UCSC

Incident wavefront

Shape of
Deformable Mirror

Corrected wavefront

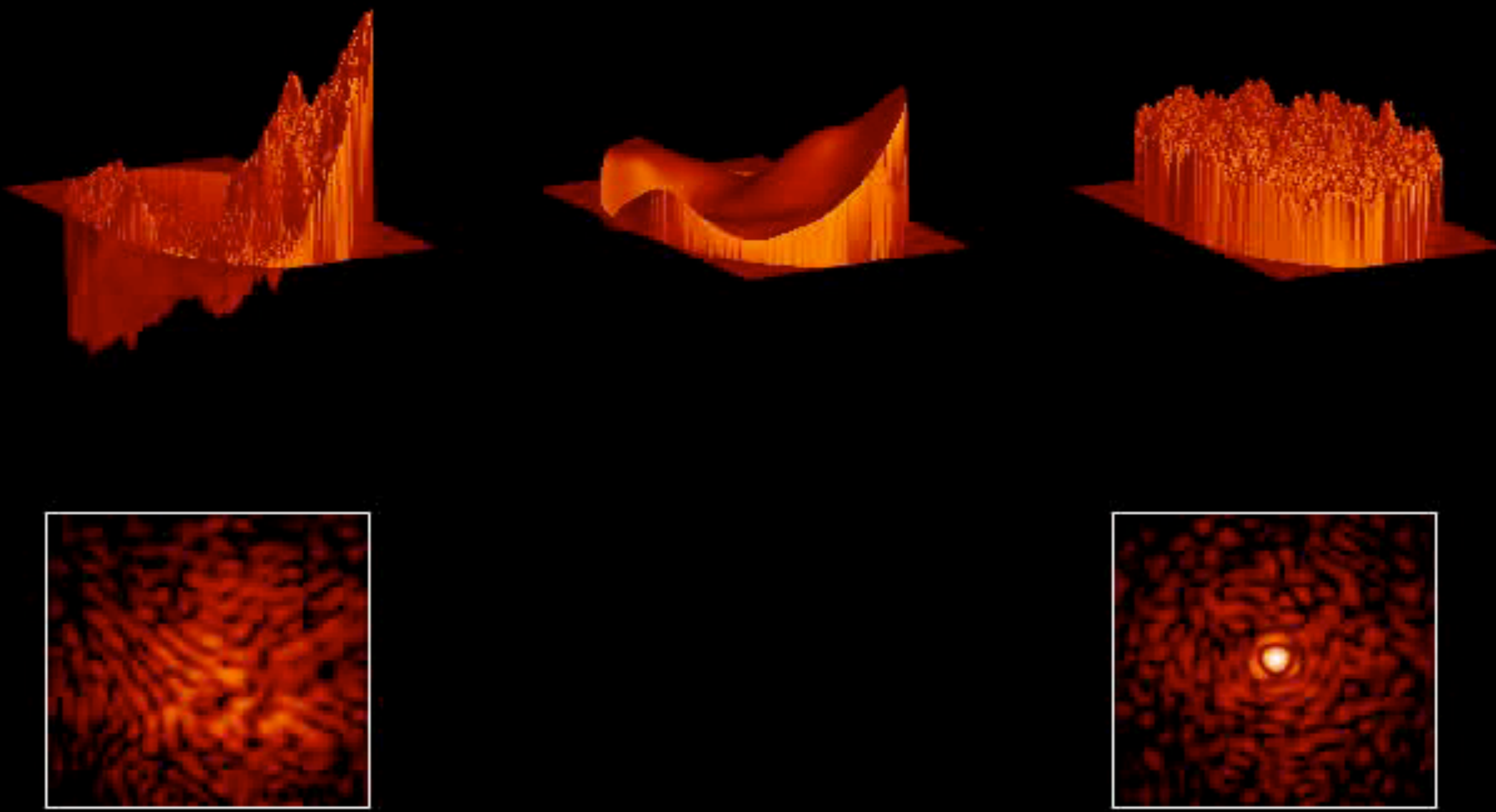


Log (intensity)

Log (intensity)

Credit: J. Lloyd

Credit: Claire E. Max, UCSC

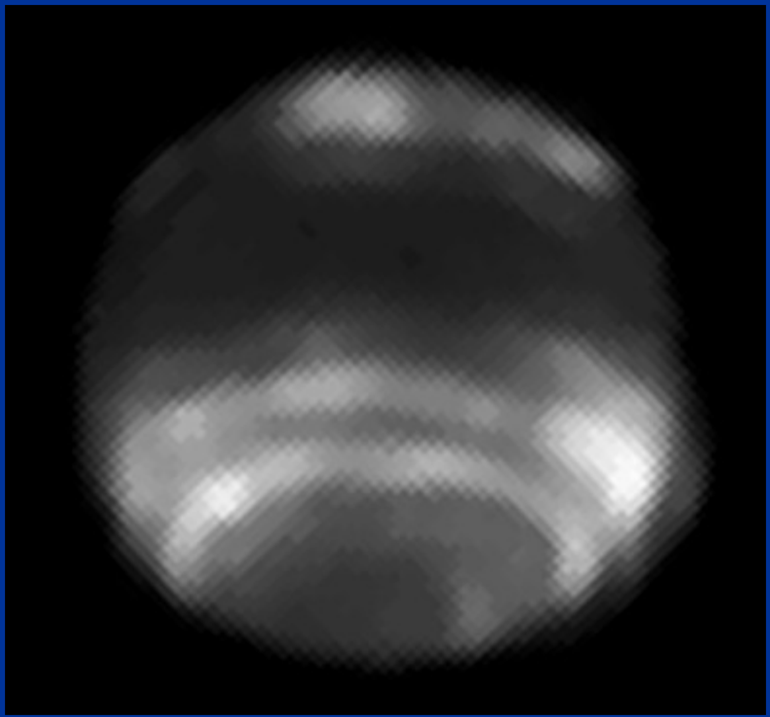


Credit: J. Lloyd

Credit: Claire E. Max, UCSC

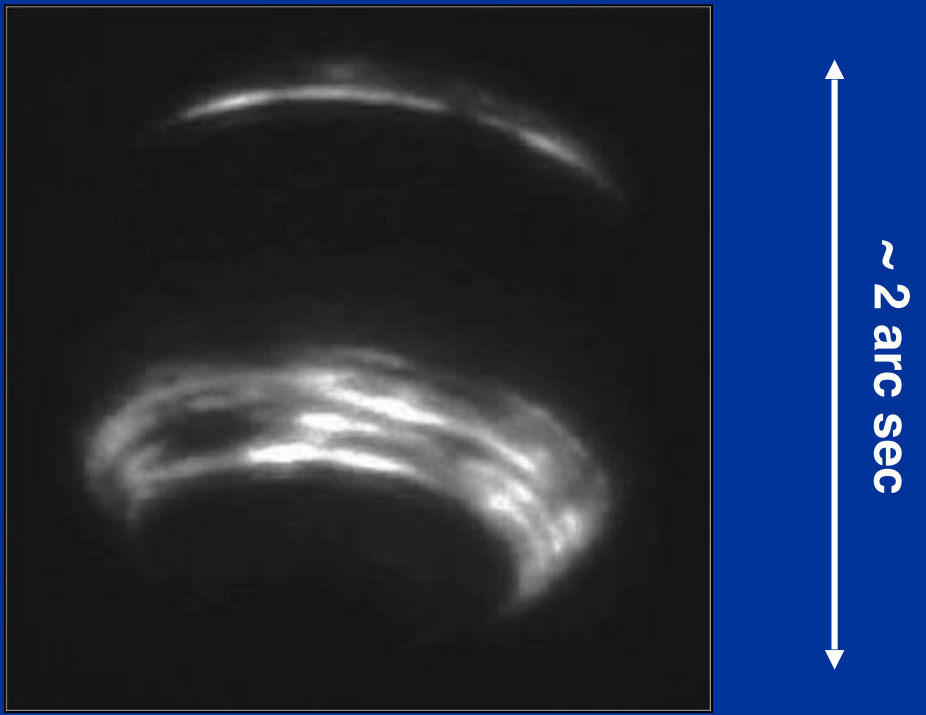
# *Neptune at 1.6 µm: Keck AO exceeds resolution of Hubble Space Telescope*

## HST - NICMOS



2.4 meter telescope

## Keck AO



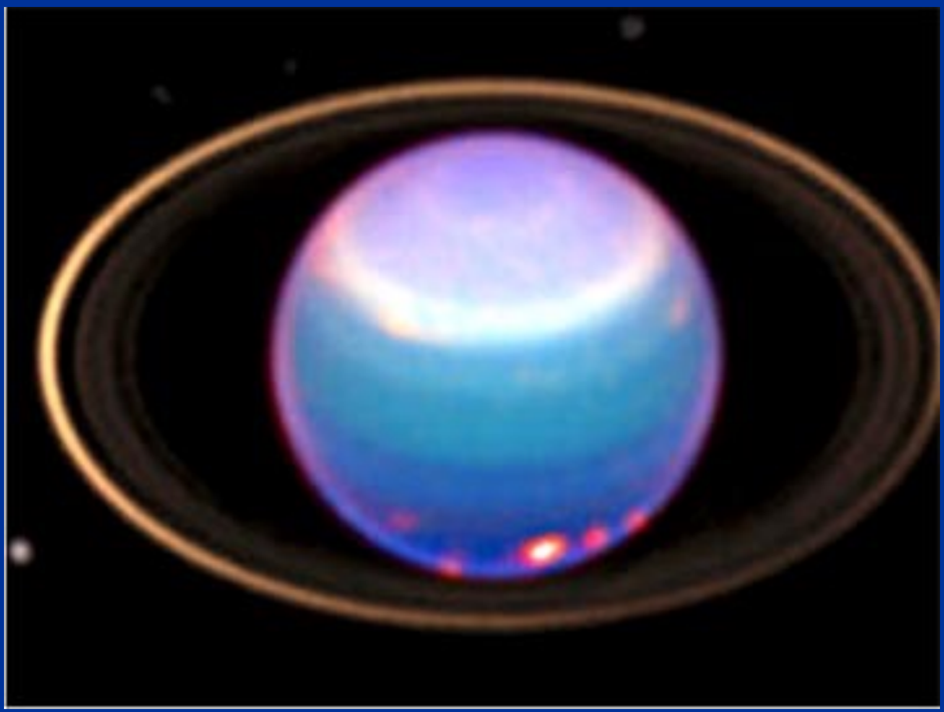

10 meter telescope

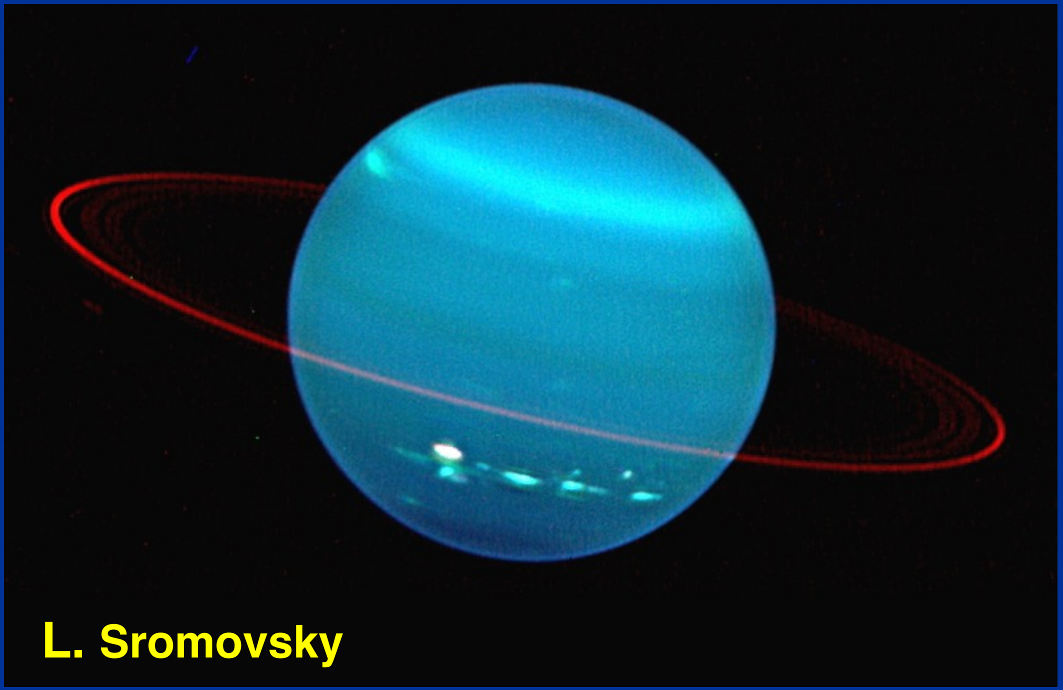
**(Two different dates and times)**



**Credit: Claire E. Max, UCSC**

# Uranus with Hubble Space Telescope and Keck AO






HST, Visible

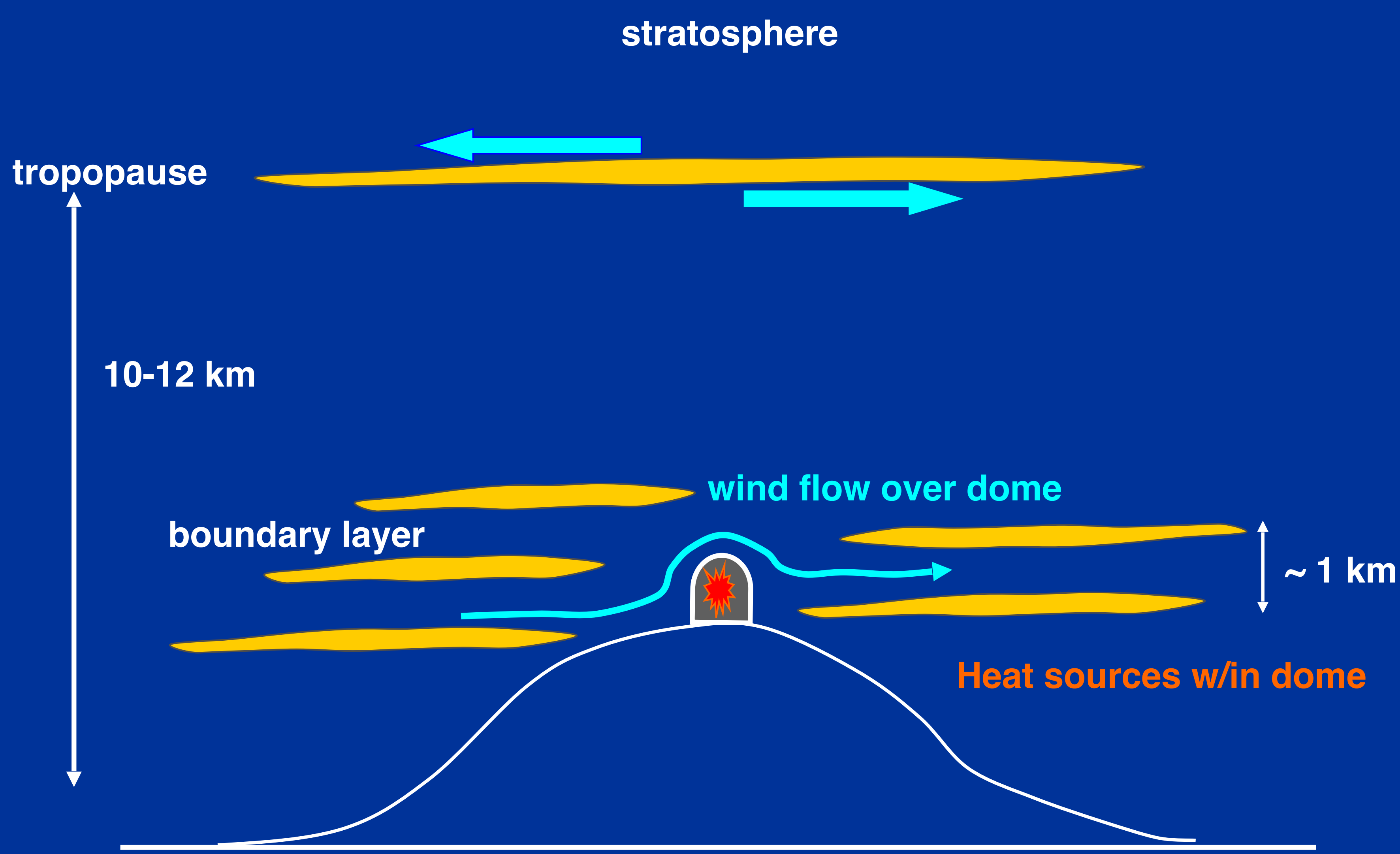
Keck AO, IR

Lesson: Keck in near IR has ~ same resolution as Hubble in visible

# Adaptive Optics

- Atmospheric Turbulence
- Sensing the wave front
- Correcting the wave front
- Laser Guide Stars
- Other types of AO systems

# Turbulence arises in many places

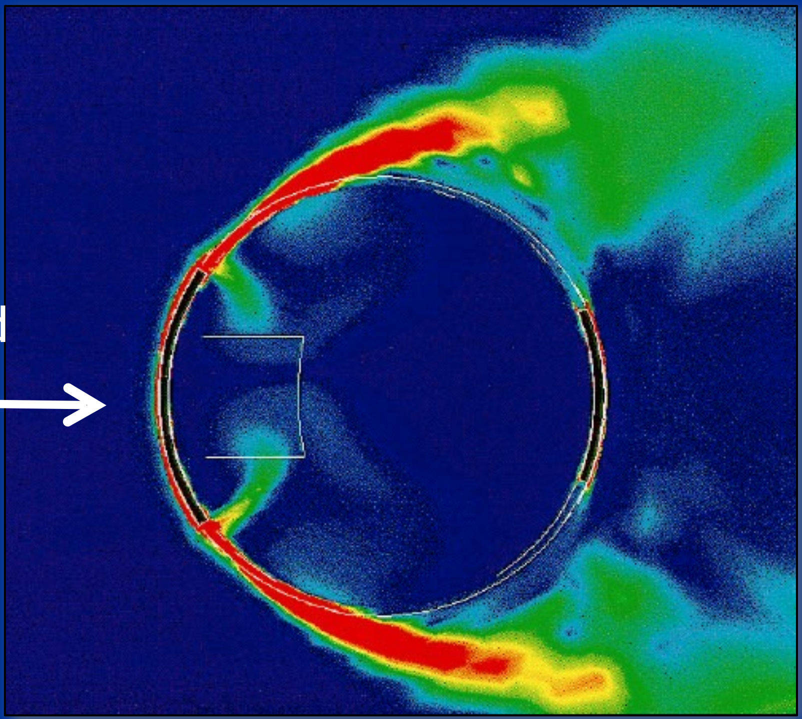




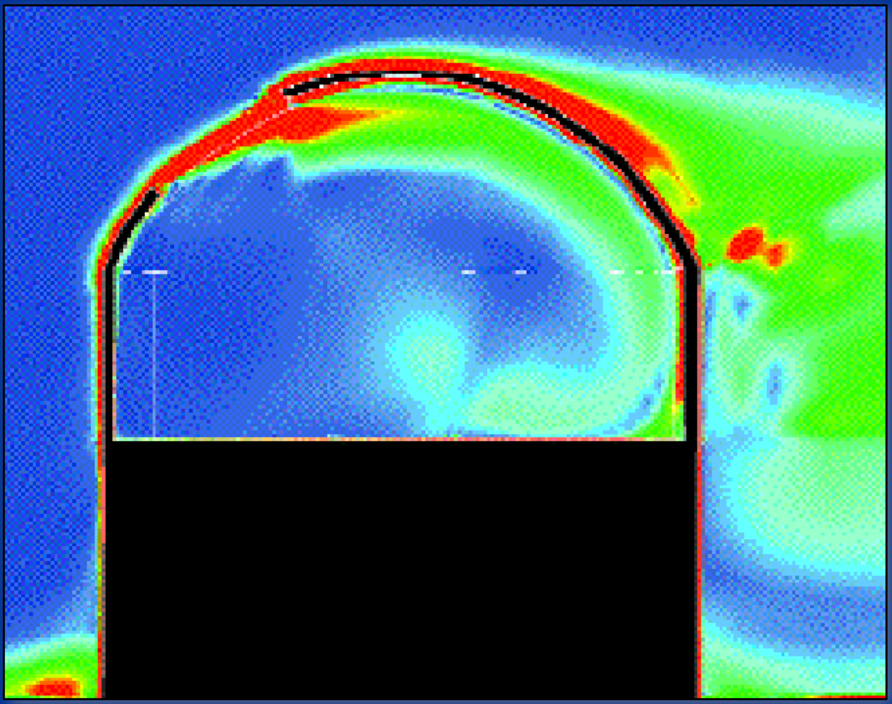

Credit: Claire E. Max, UCSC

# *Turbulence arises from wind flowing over the telescope dome*

Wind



Top view



Side view

Computational fluid dynamics simulation (D. de Young)



**Credit: Claire E. Max, UCSC**

# Sometimes clouds show great Kelvin-Helmholtz vortex patterns

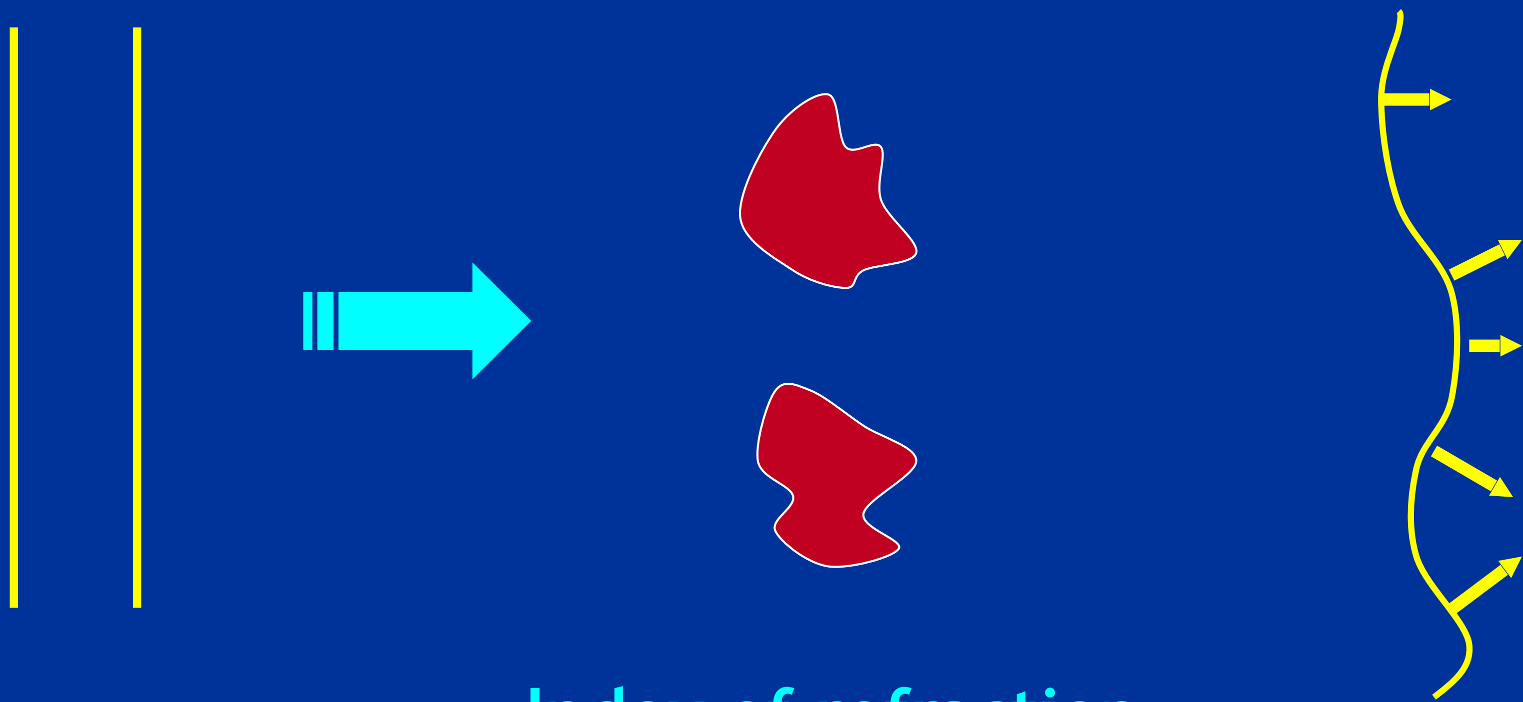
A clear sign of wind shear



Credit: Claire E. Max, UCSC

## *Atmospheric perturbations cause distorted wavefronts*

Rays not parallel



Plane Wave

Index of refraction variations

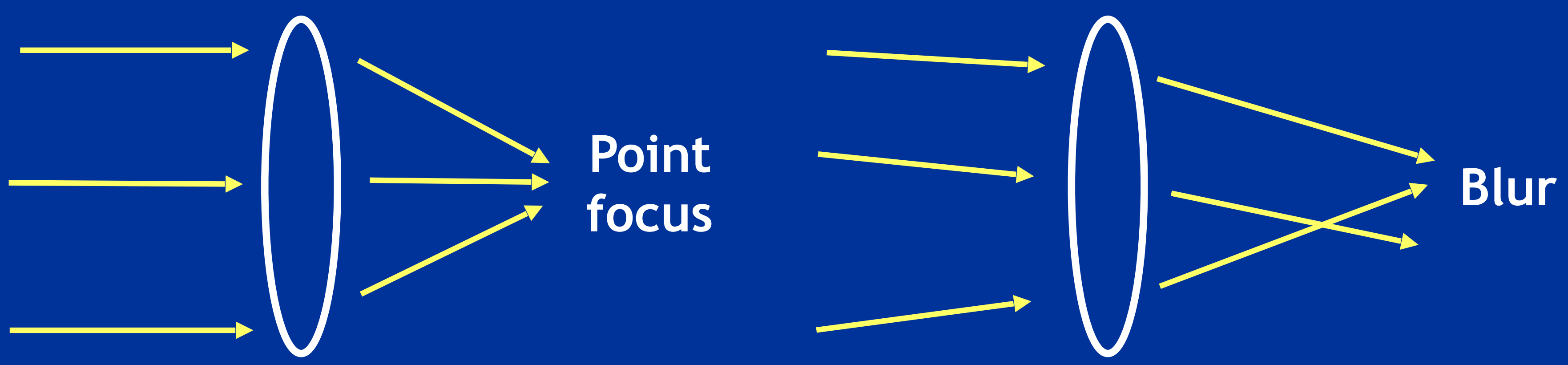
Distorted Wavefront



Credit: Claire E. Max, UCSC

# *Optical consequences of turbulence*

- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel
- Hence rays can't be focused to a point:



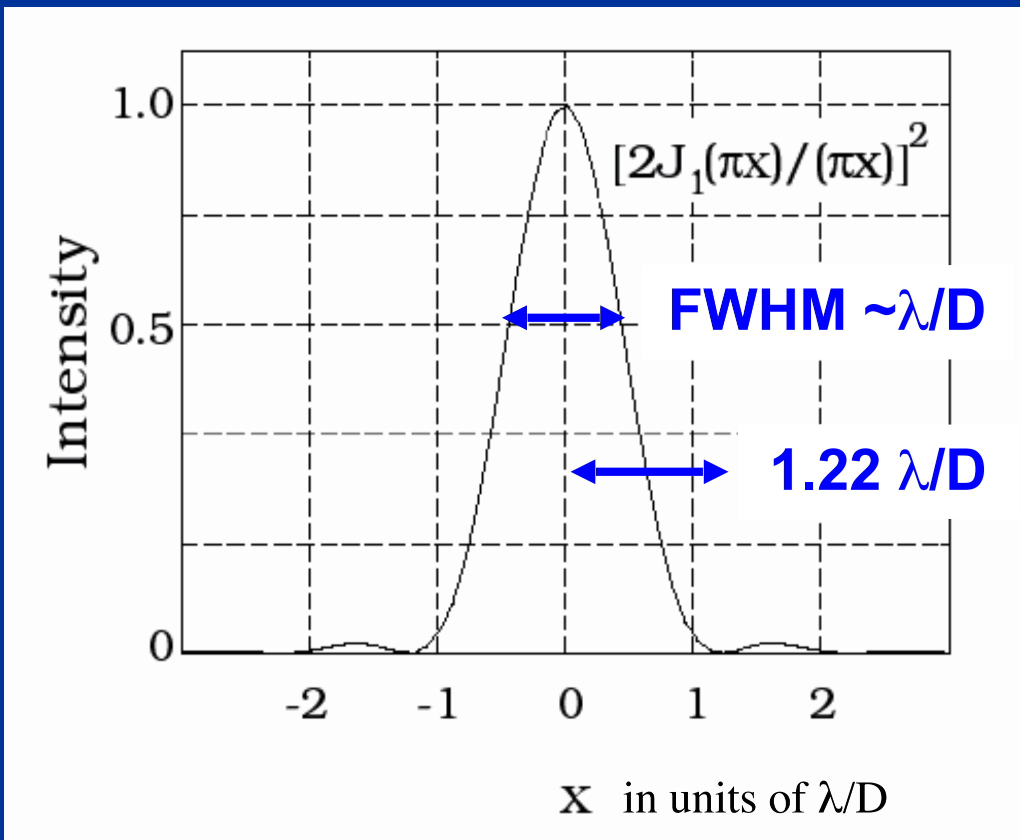

Parallel light rays

Light rays affected by turbulence



Credit: Claire E. Max, UCSC

# Imaging through a perfect telescope




Point Spread Function (PSF): intensity profile from point source

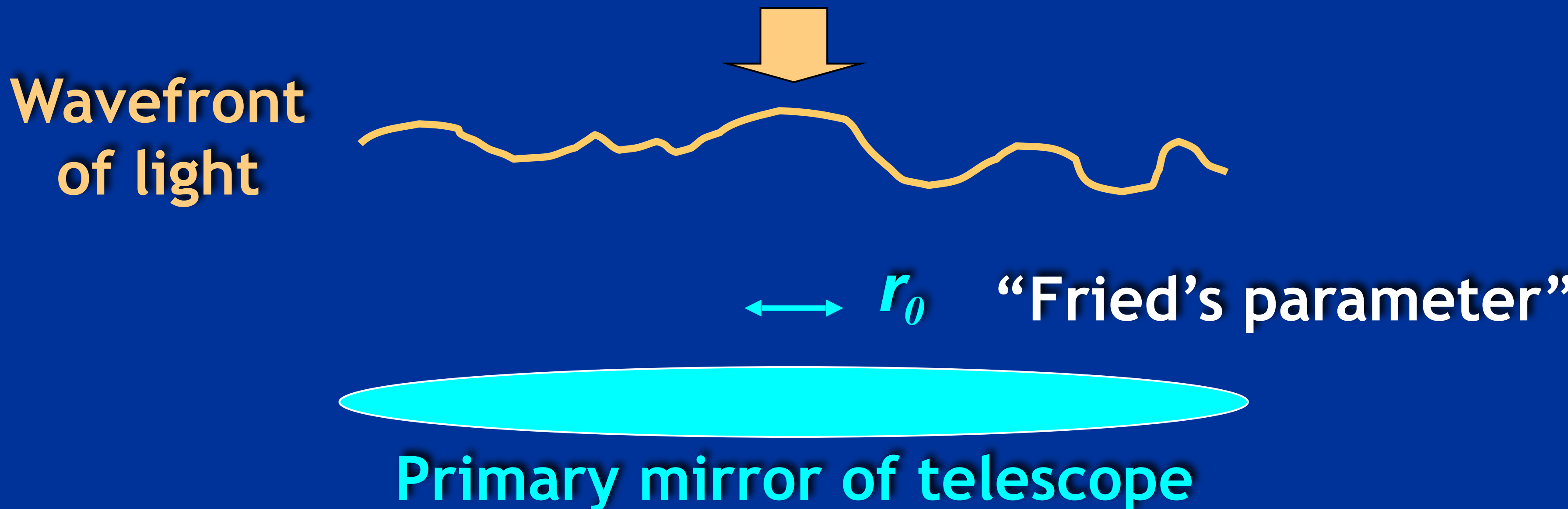
With no turbulence, FWHM is diffraction limit of telescope, $\theta \sim \lambda / D$

Example:

$\lambda / D$ = 0.02 arc sec for $\lambda$ = 1 μm, $D$ = 10 m

With turbulence, image size gets much larger (typically 0.5 - 2 arc sec)

# *Characterize turbulence strength by quantity $r_0$*




- “Coherence Length” $r_0$: distance over which optical phase distortion has mean square value of 1 rad$^2$ ($r_0$ ~ 15 - 30 cm at good observing sites)

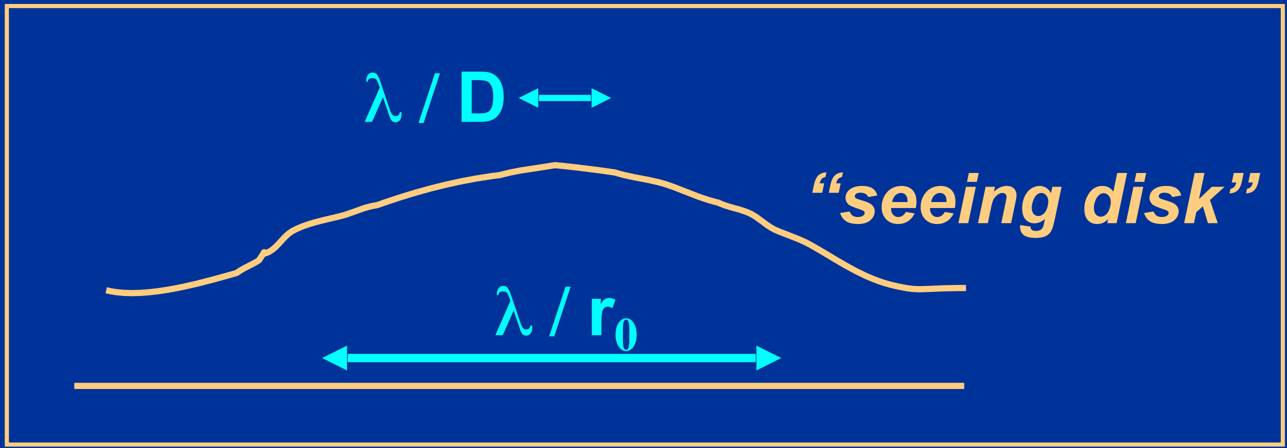
- $r_0$ = 10 cm \ FWHM = 1 arc sec at $\lambda$ = 0.5 μm



Credit: Claire E. Max, UCSC

# *Effect of turbulence on image size*

- If telescope diameter D >> $r_0$ , image size of a point source is $\lambda / r_0 \gg \lambda / D$




- $r_0$ is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.

- Any telescope with diameter D > $r_0$ has no better spatial resolution than a telescope for which D = $r_0$ (!)



Credit: Claire E. Max, UCSC

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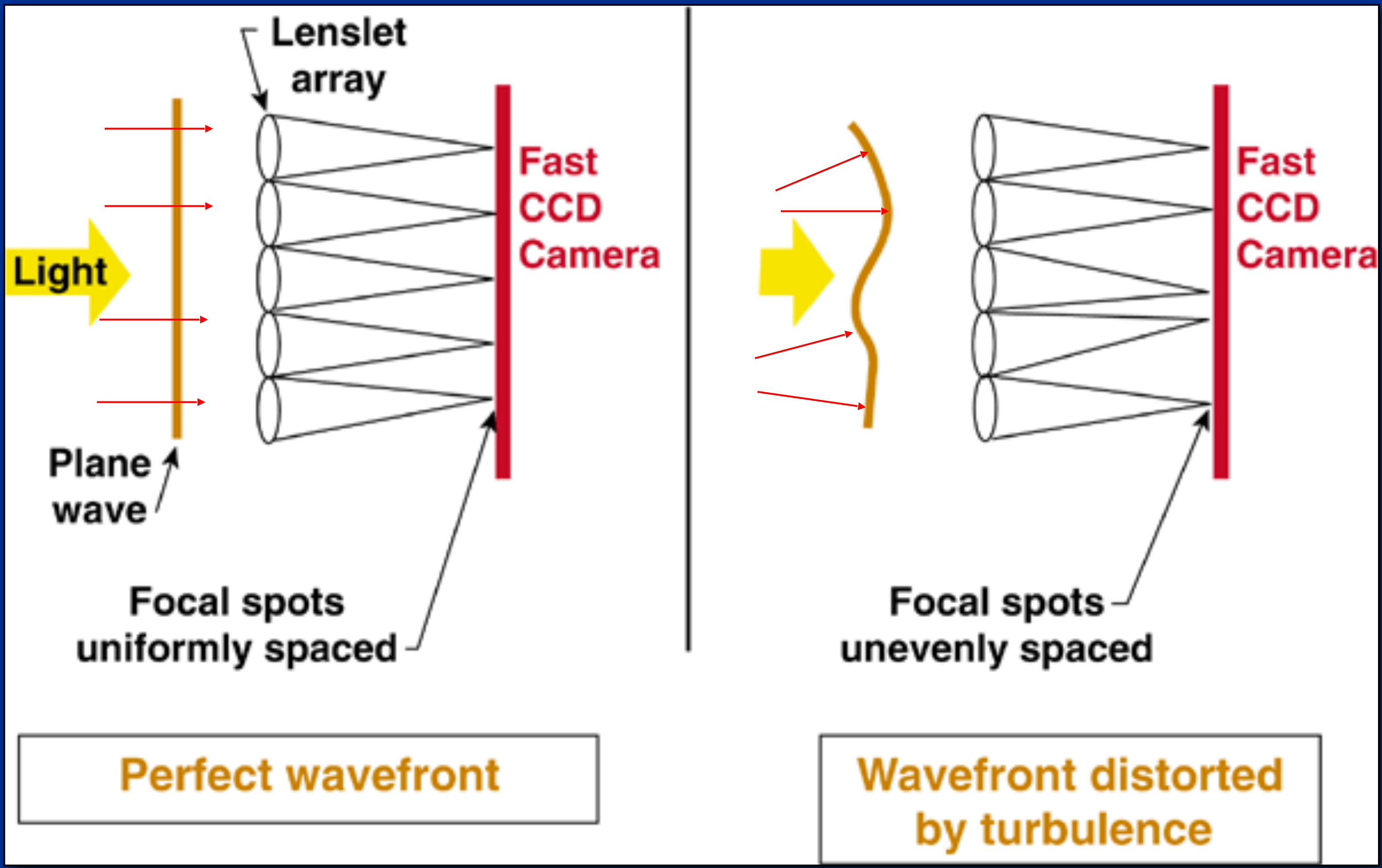
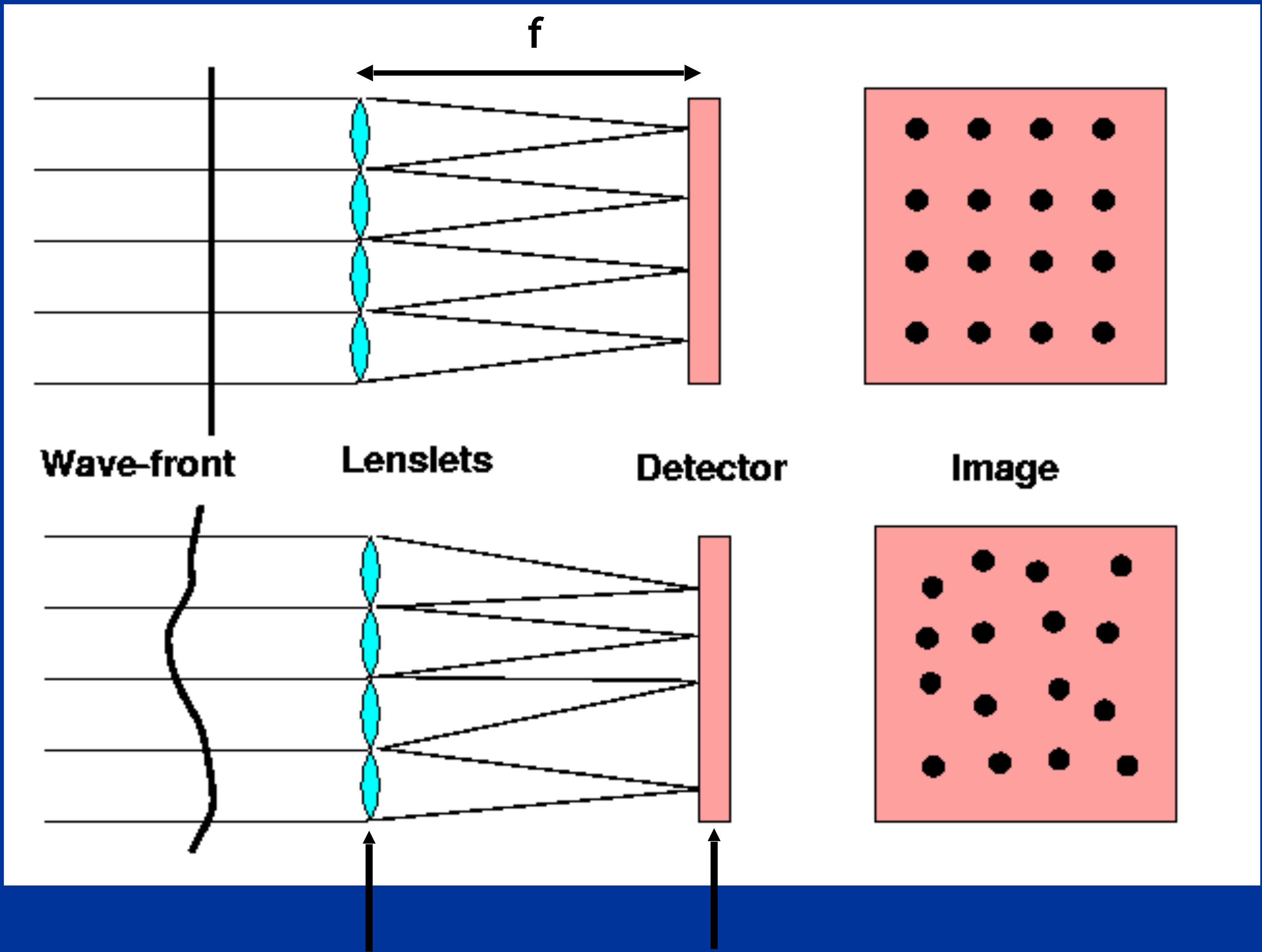
# *How to measure turbulent distortions (one method among many)*




Shack-Hartmann wavefront sensor

Credit: Claire E. Max, UCSC

# Shack-Hartmann wavefront sensor concept - measure subaperture tilts




Pupil plane

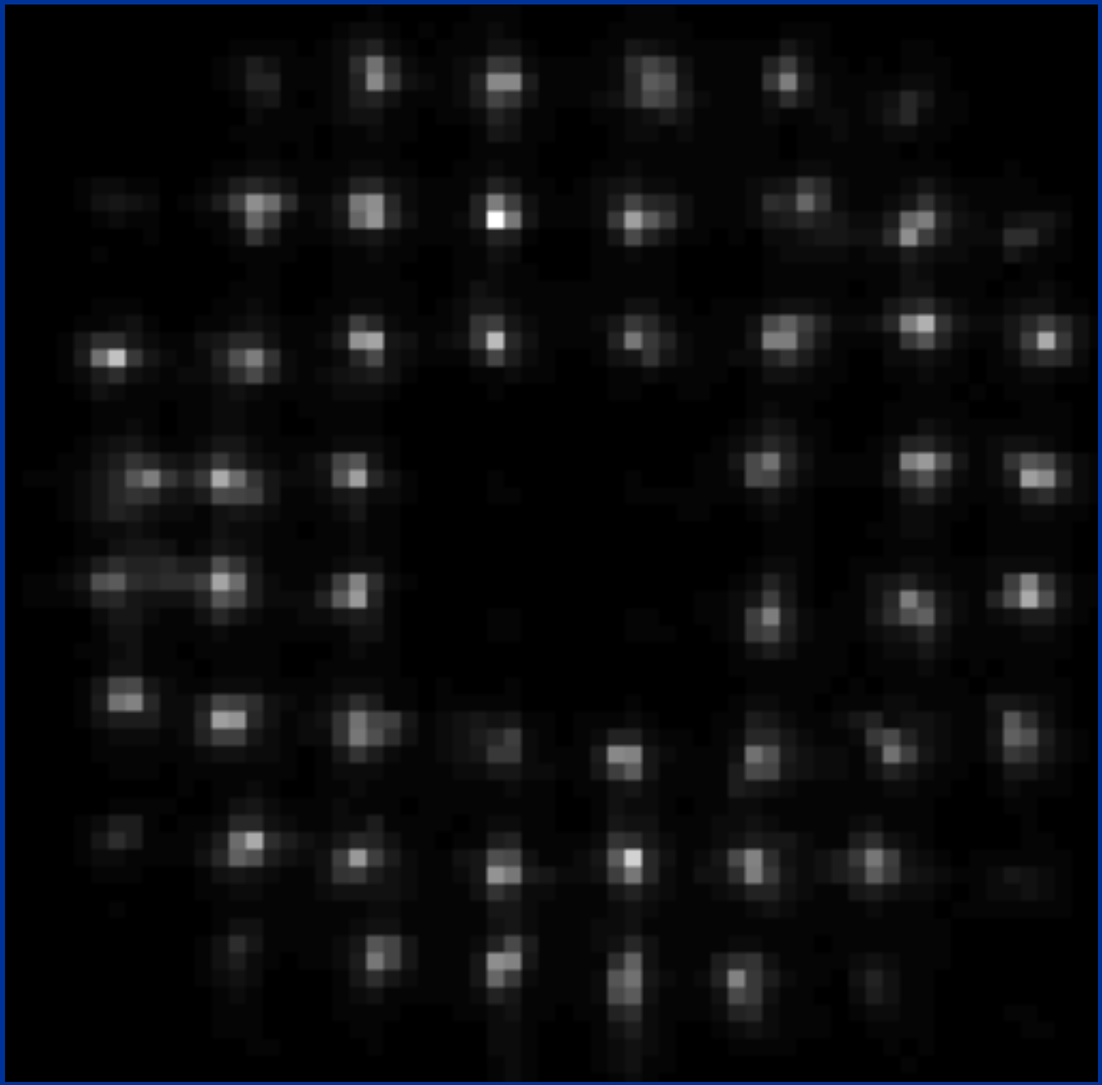
Image plane

Credit:
A. Tokovinin



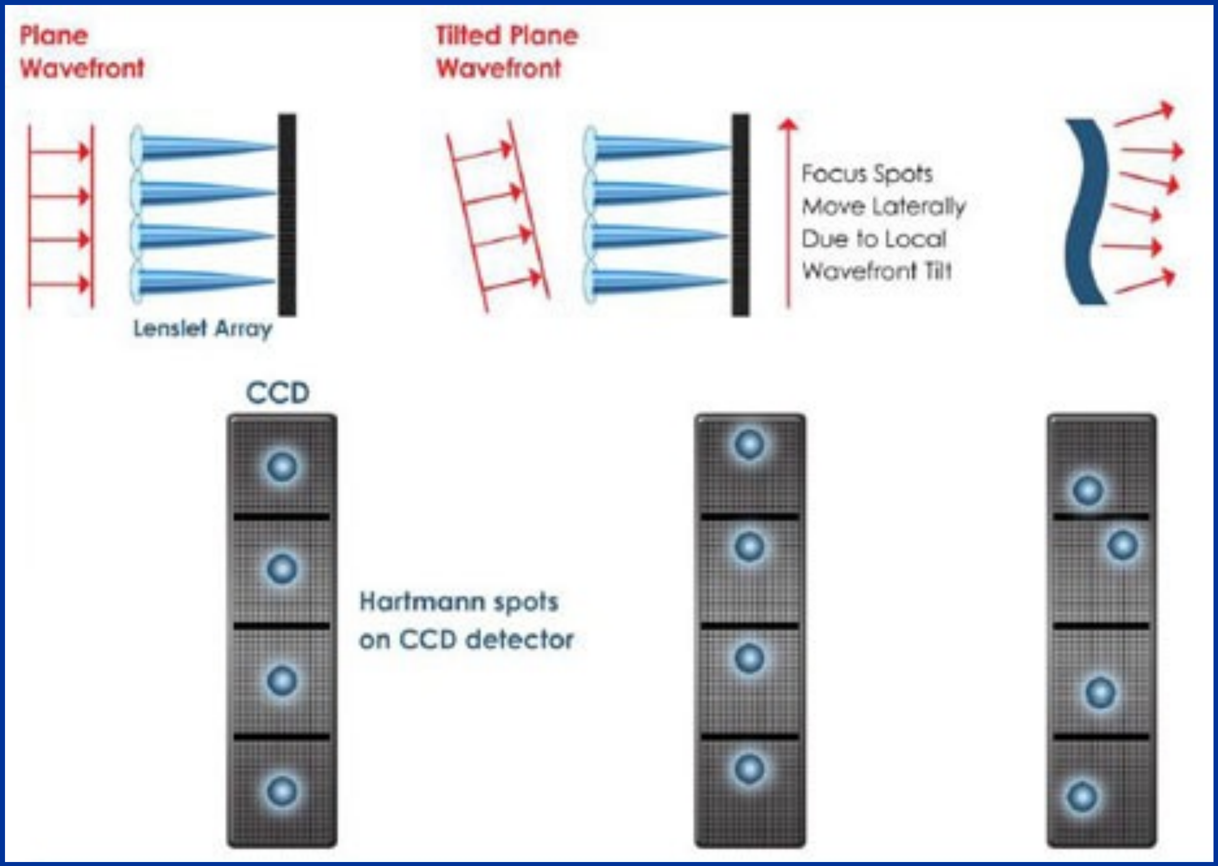
Credit: Claire E. Max, UCSC

# *Example: Shack-Hartmann Wavefront Signals*



Credit: Cyril Cavadore

# *Notional Shack-Hartmann Sensor spots*




Credit: Boston Micromachines

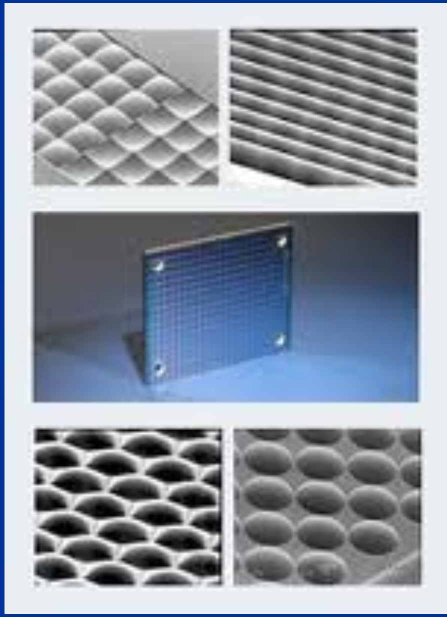


**Credit: Claire E. Max, UCSC**

# *Example: Keck adaptive optics system*

- Telescope diameter D = 10 m,
  M = 2800 ⇒ size of whole lenslet array =
  10/2800 m = 3.57 x $10^{-3}$ m = 3.57mm
- Lenslet array is approx. 18 x 18 lenslets ⇒
  each lenslet is ~ 200 microns in diameter

✓ Sanity check: size of subaperture on telescope mirror = lenslet diameter x magnification = 200 microns x 2800 = 56 cm ~ $r_0$ for wavelength λ between 1 and 2 microns

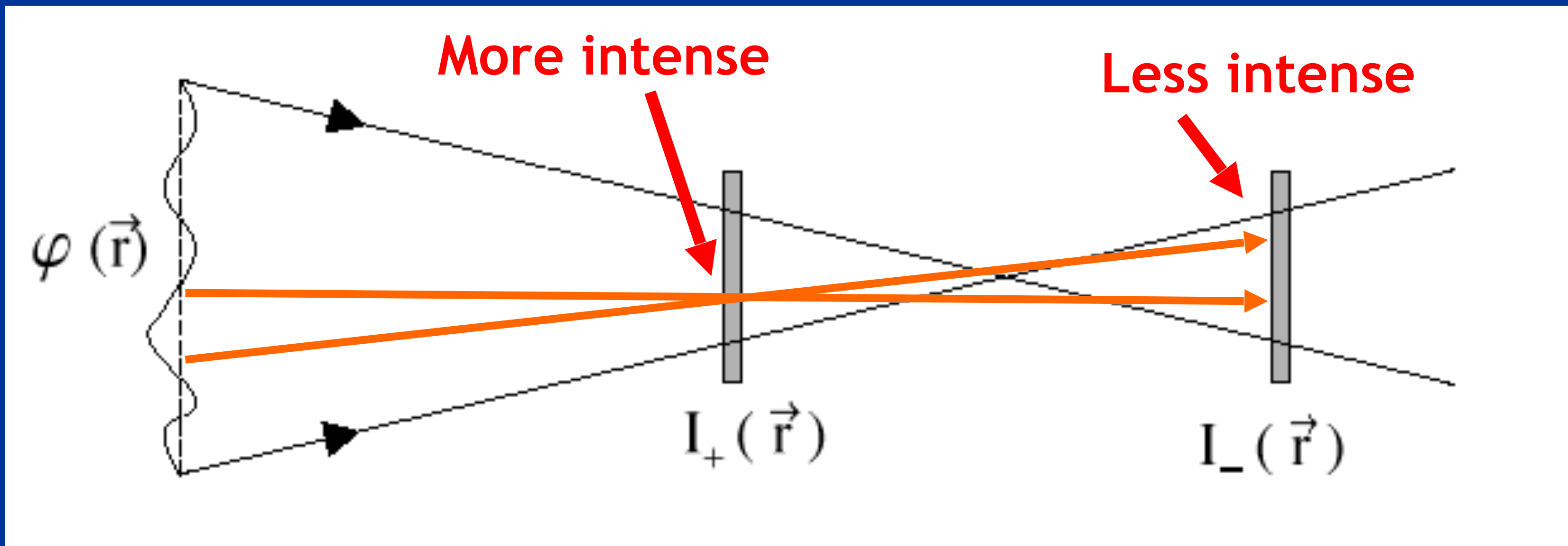


Some examples of micro-lenslet arrays



Credit: Claire E. Max, UCSC

# *Practical implementation of curvature sensing*




- Use oscillating membrane mirror (2 kHz!) to vibrate rapidly between $I_+$ and $I_-$ extrafocal positions
- Measure intensity in each subaperture with an "avalanche photodiode" (only need one per subaperture!)
  - Detects individual photons, no read noise, QE ~ 60%
  - Can read out very fast with no noise penalty



**Credit: Claire E. Max, UCSC**

# Pyramid sensing

- From Andrei Tokovinin's tutorial

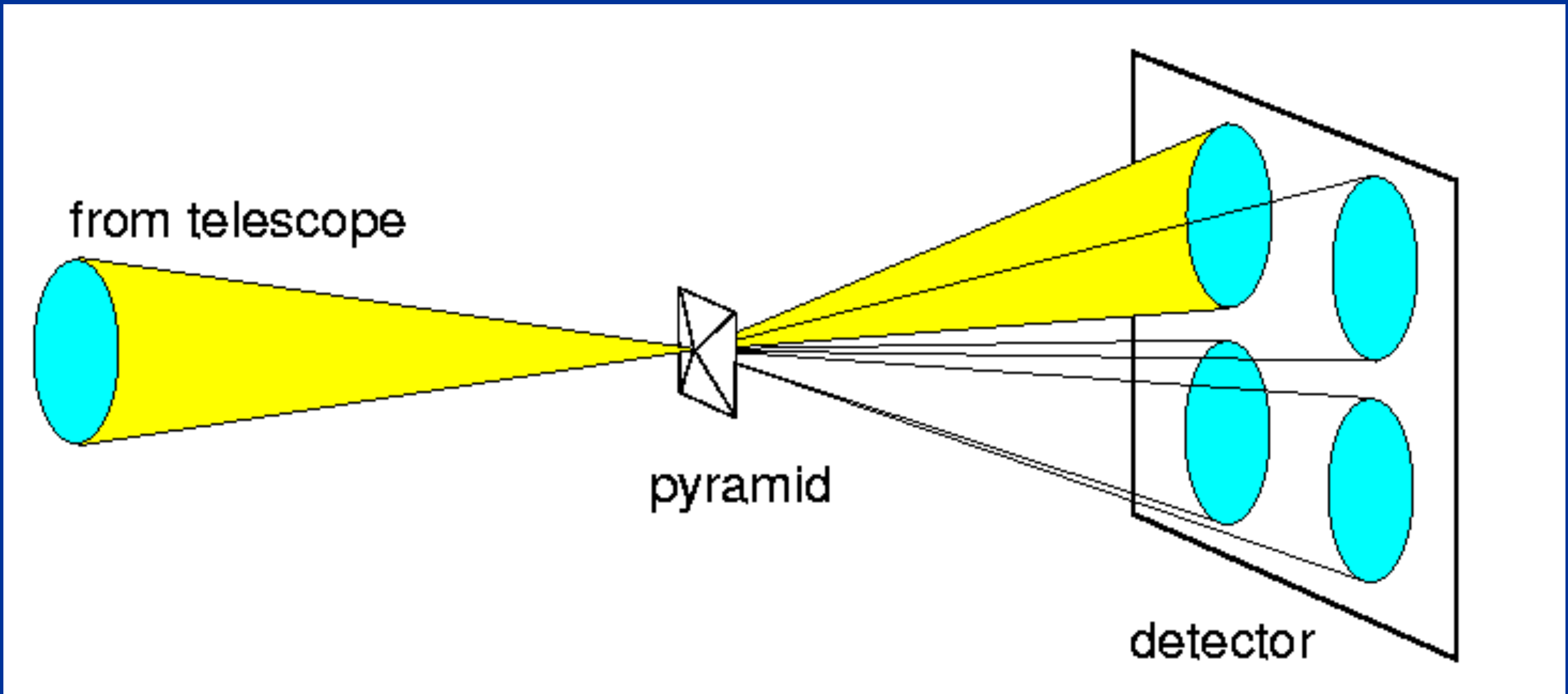



Image plane Pupil plane

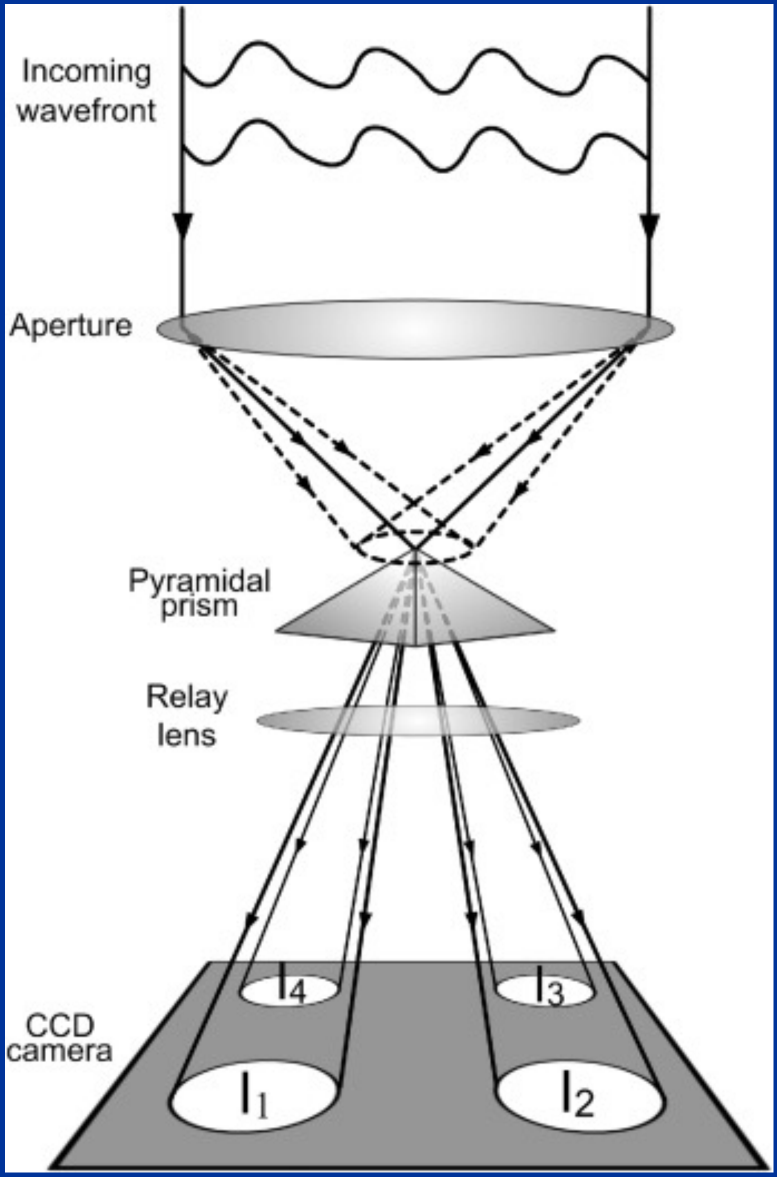


Credit: Claire E. Max, UCSC

# Pyramid for the William Herschel Telescope's AO system


Credit: Claire E. Max, UCSC

# Schematic of pyramid sensor




Credit: Iuliia Shatokhina et al.



Credit: Claire E. Max, UCSC

# Pyramid sensor reverses order of operations in a Shack-Hartmann sensor

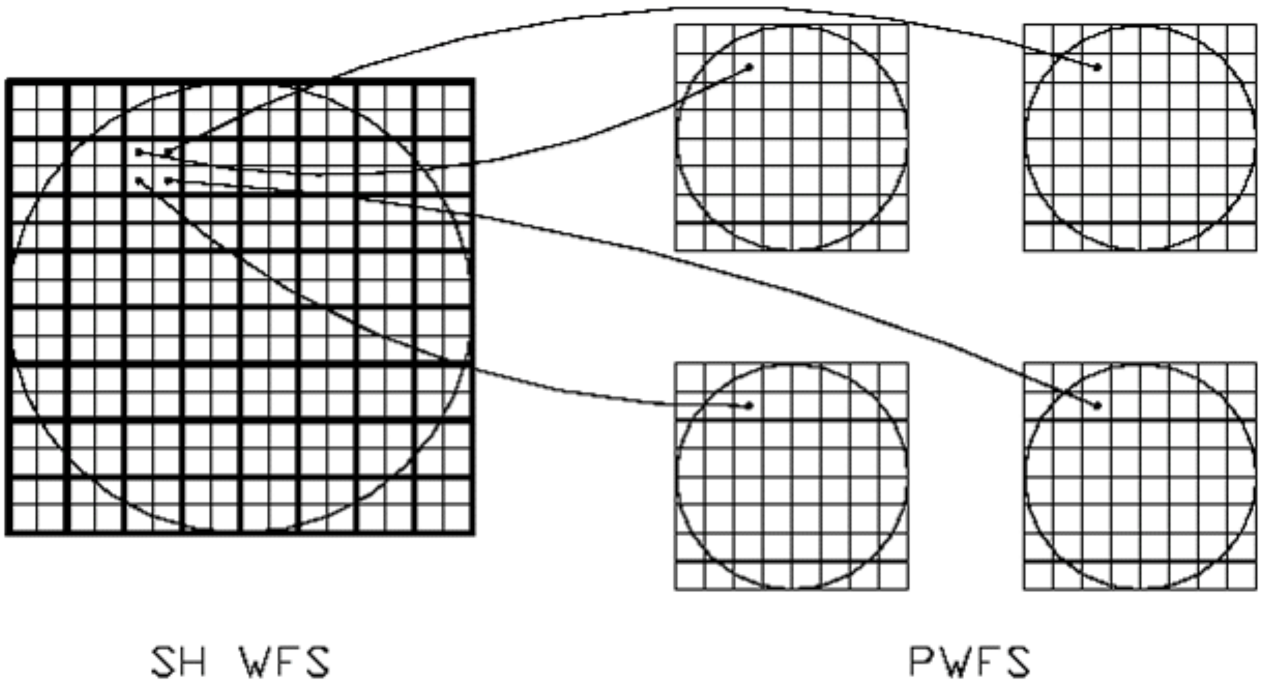



Figure 3- 4: Organization of SH wavefront data (left) versus pyramid wavefront data (right). The circle indicates the beam footprint on the WFS. The heavily-weighted squares on the left indicate the various subapertures (8x8 grid of subapertures). Each subaperture has 4 pixels (a quad cell). In a pyramid wavefront sensing scheme, each pixel represents a subaperture; the 4 images of the pupil correspond to the quadrants of the quad cell.



Credit: Claire E. Max, UCSC

# *Potential advantages of pyramid wavefront sensors*

- Wavefront measurement error can be much lower
  - Shack-Hartmann: size of spot limited to $\lambda$ / d, where d is size of a sub-aperture and usually d ~ $r_0$
  - Pyramid: size of spot can be as small as $\lambda$ / D, where D is size of whole telescope. So spot can be $D/r_0$ = 20 - 100 times smaller than for Shack-Hartmann
  - Measurement error (e.g. centroiding) is proportional to spot size/SNR. Smaller spot = lower error.
- Avoids bad effects of charge diffusion in CCD detectors
  - Fuzzes out edges of pixels. Pyramid doesn't mind as much as S-H.



Credit: Claire E. Max, UCSC

# *Summary of main points*

- Wavefront sensors in common use for astronomy measure intensity variations, deduce phase. Complementary.
  - Shack-Hartmann
  - Curvature sensors
- Curvature systems: cheaper, fewer degrees of freedom, scale more poorly to high no. of degrees of freedom, but can use fainter guide stars
- Shack-Hartmann systems excel at very large no. of degrees of freedom
- New kid on the block: pyramid sensors
  - Very successful for fainter natural guide stars

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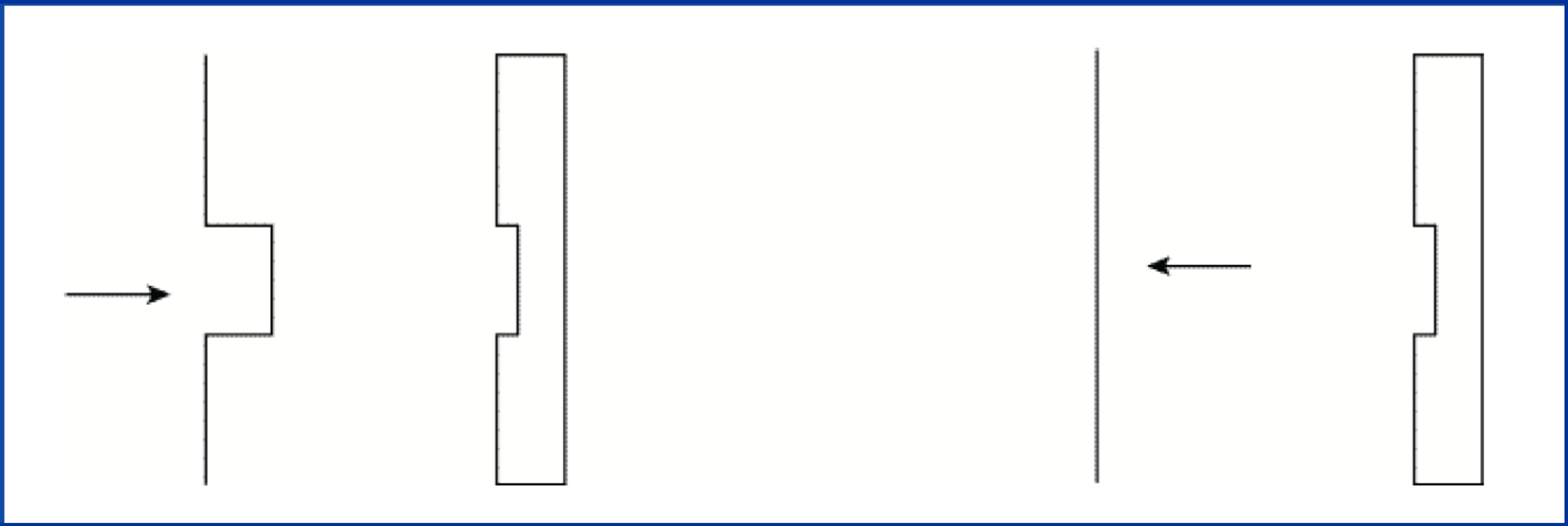
# *How a deformable mirror works (idealization)*

**BEFORE** **AFTER**



**Incoming Wave with Aberration**

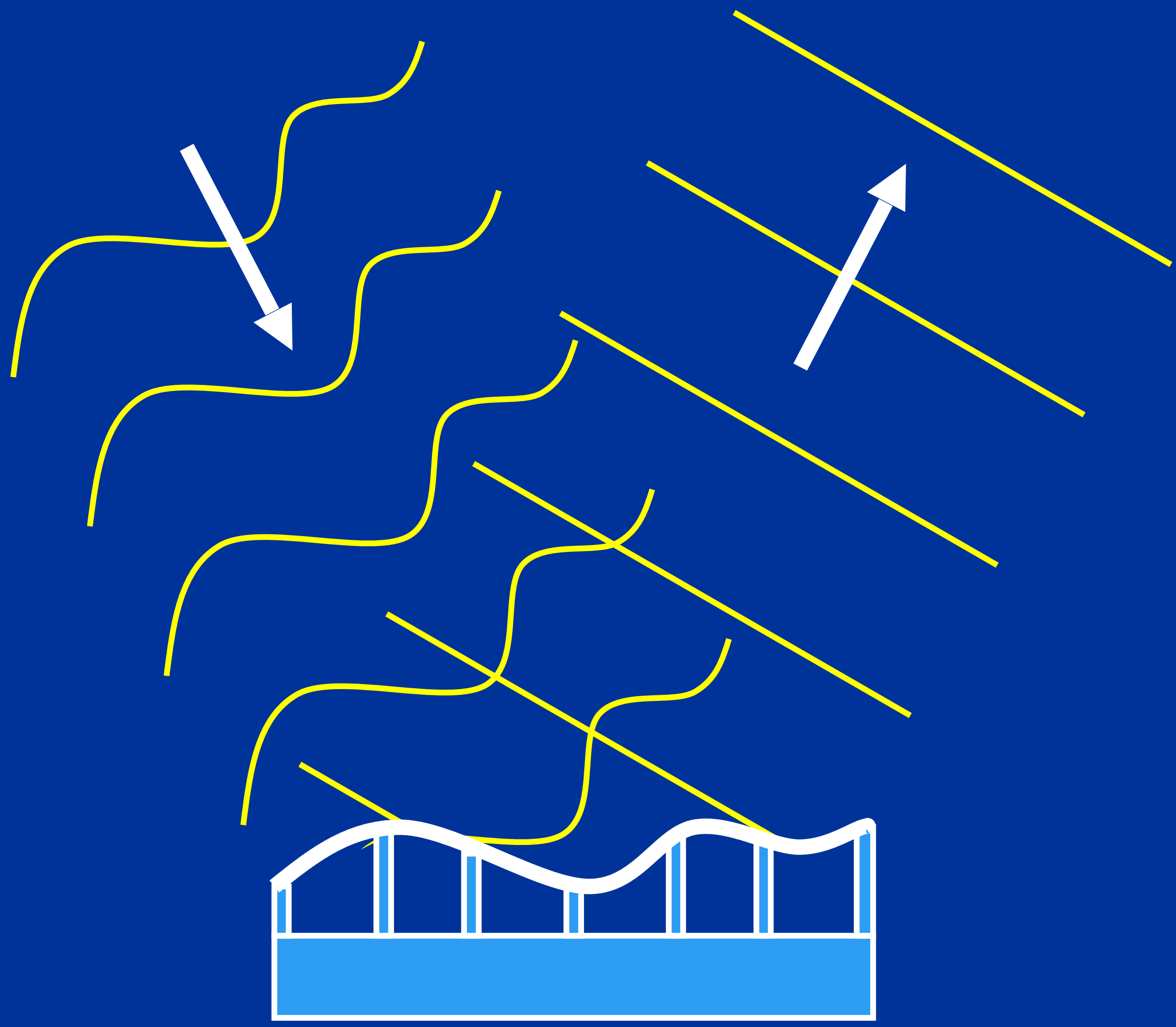
**Deformable Mirror**

**Corrected Wavefront**



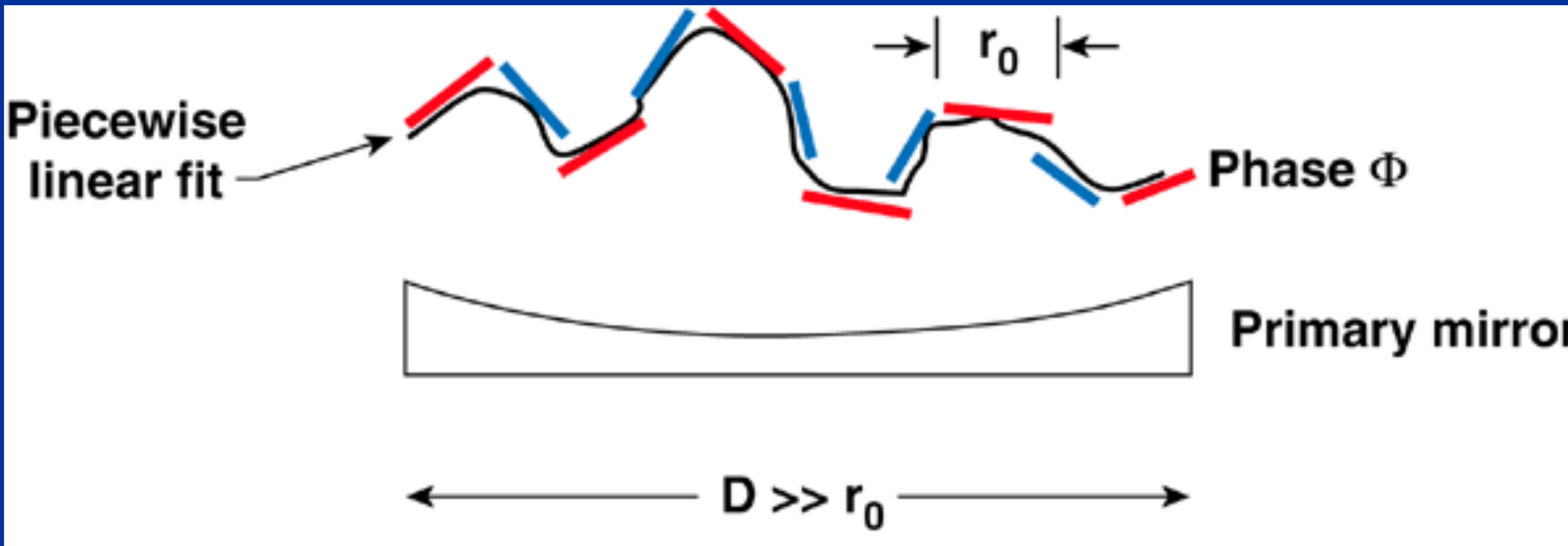
**Credit: Claire E. Max, UCSC**

# Deformable Mirror for Real Wavefronts



Credit: Claire E. Max, UCSC

# *Real deformable mirrors have smooth surfaces*



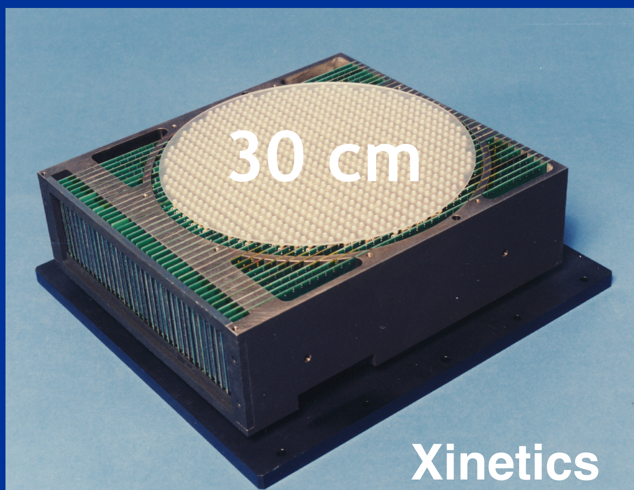

- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed <u>after</u> the main telescope mirror

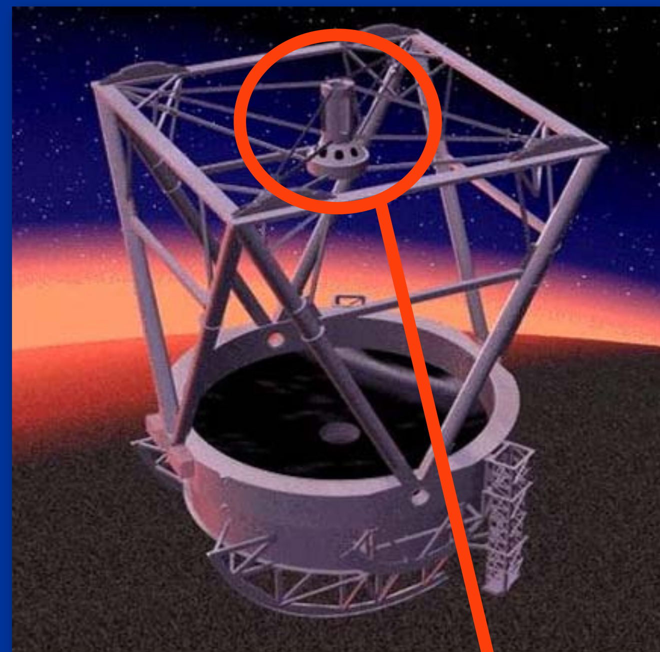


Credit: Claire E. Max, UCSC

# *Deformable mirrors come in many sizes*

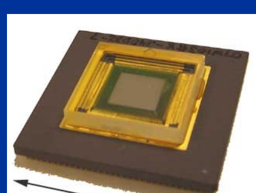
Glass facesheet
1000 actuators



Adaptive Secondary Mirrors

MEMS
1000 actuators

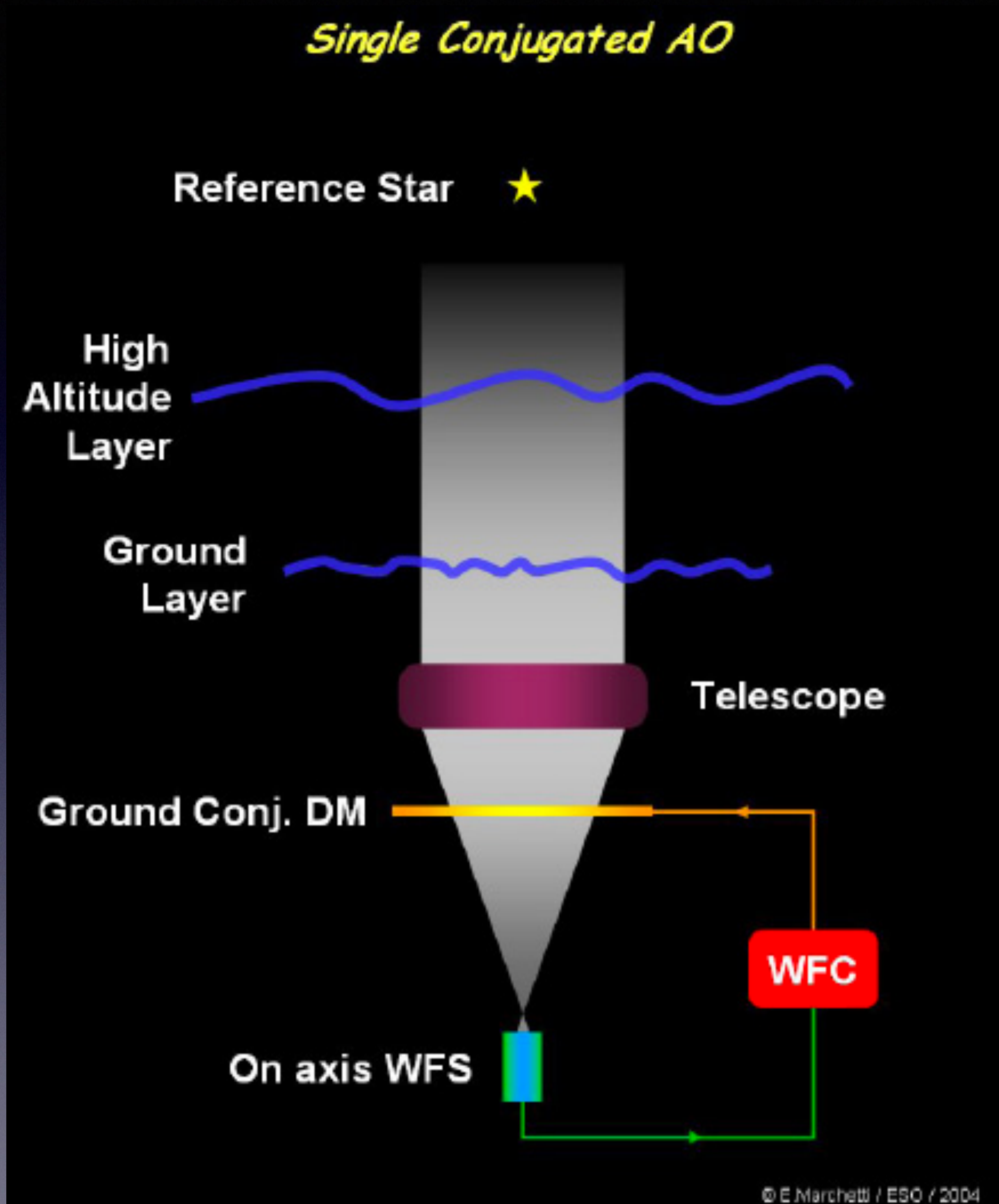


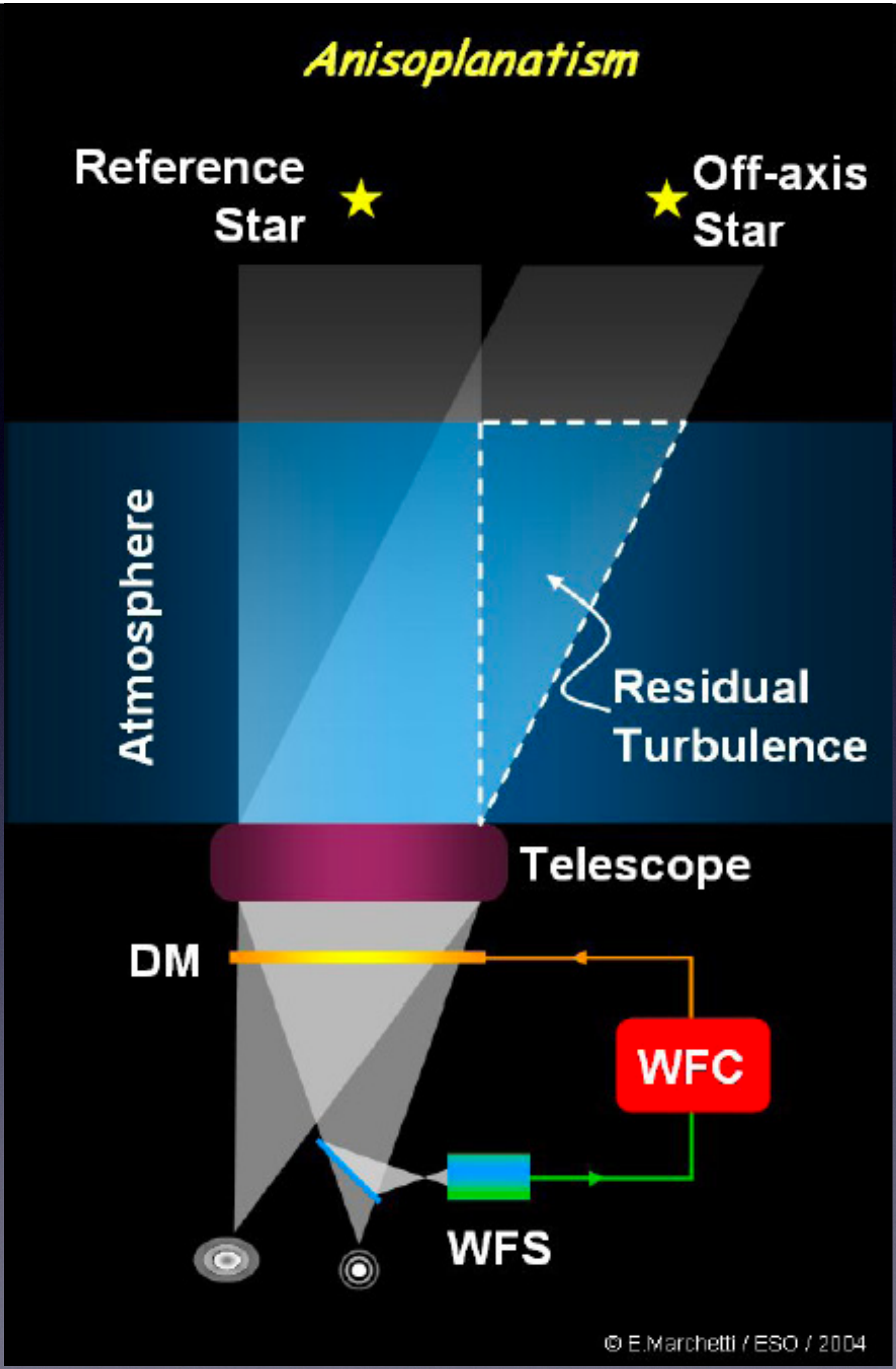
1 cm

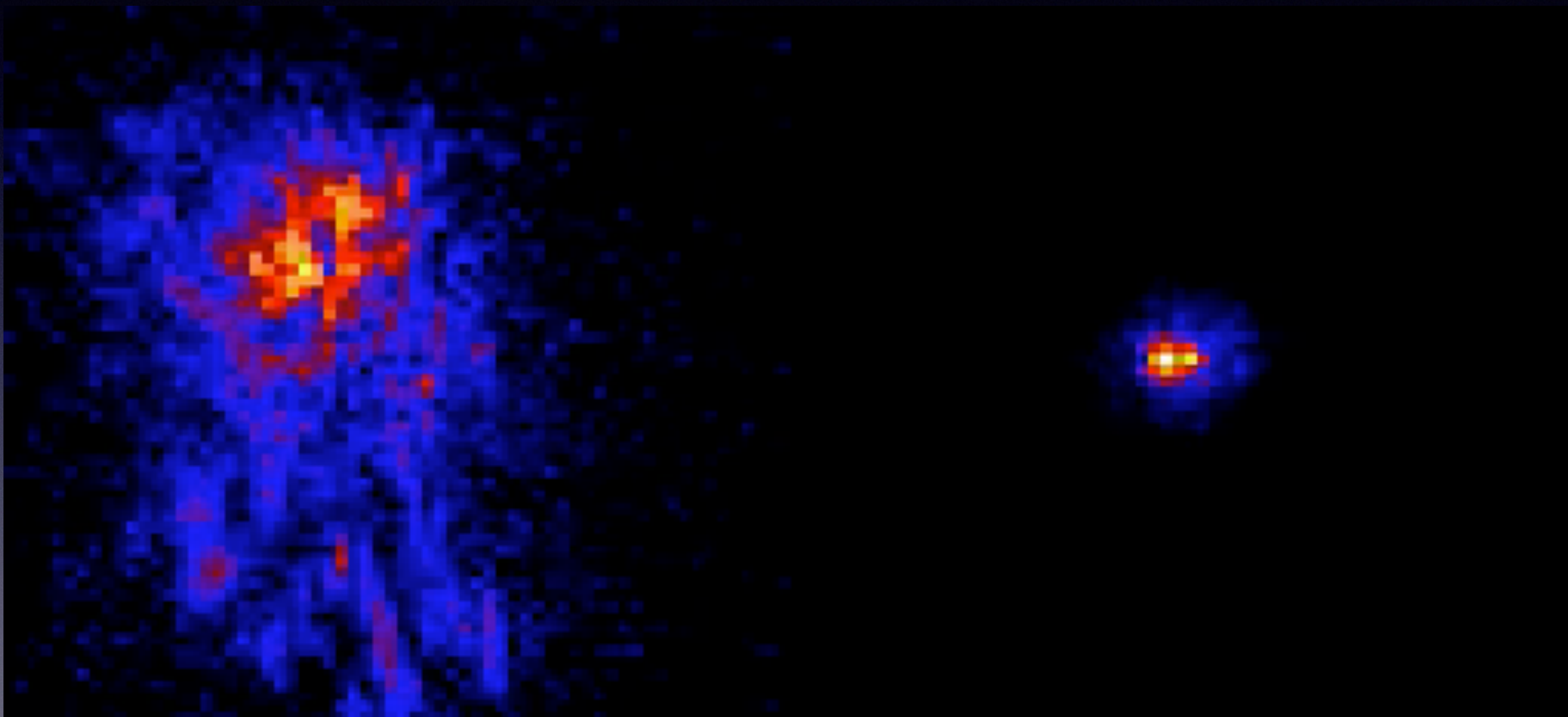
Boston Micro-Machines

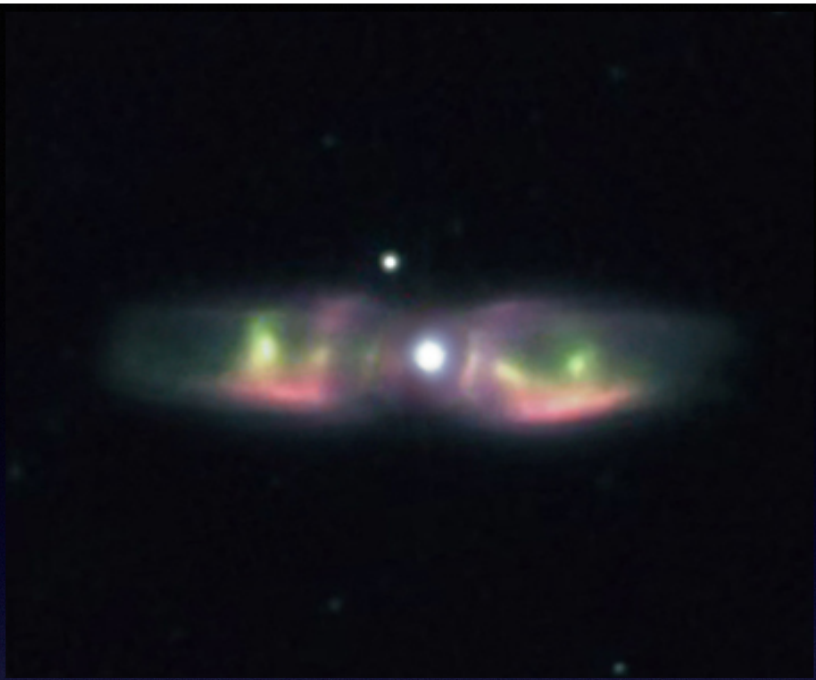


Credit: Claire E. Max, UCSC

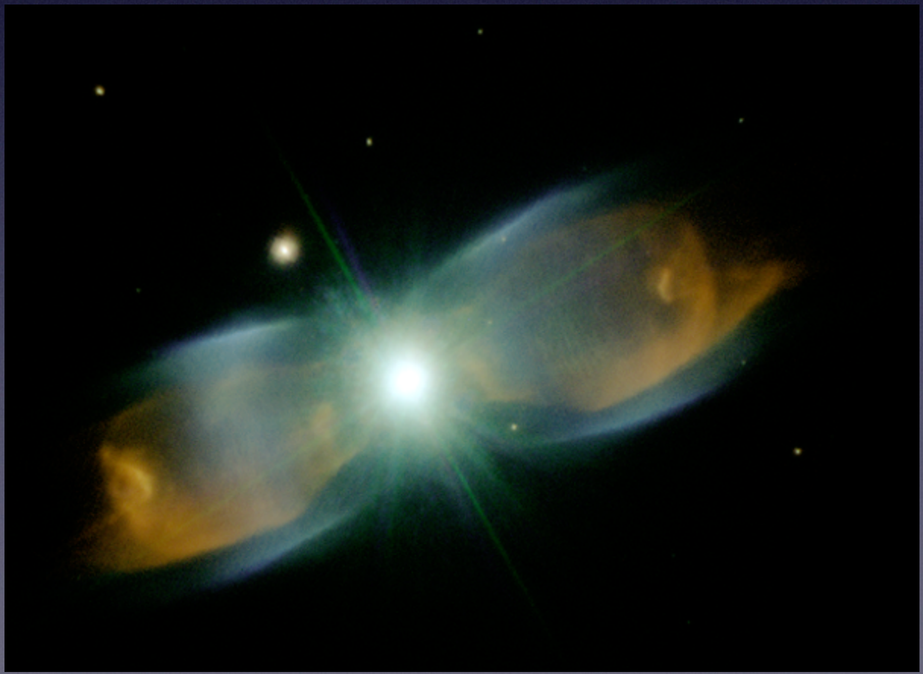

Single Conjugated AO
Reference Star
High
Altitude
Layer
Ground
Layer
Telescope
Ground Conj. DM
WFC
On axis WFS
© E.Marchetti / ESO / 2004

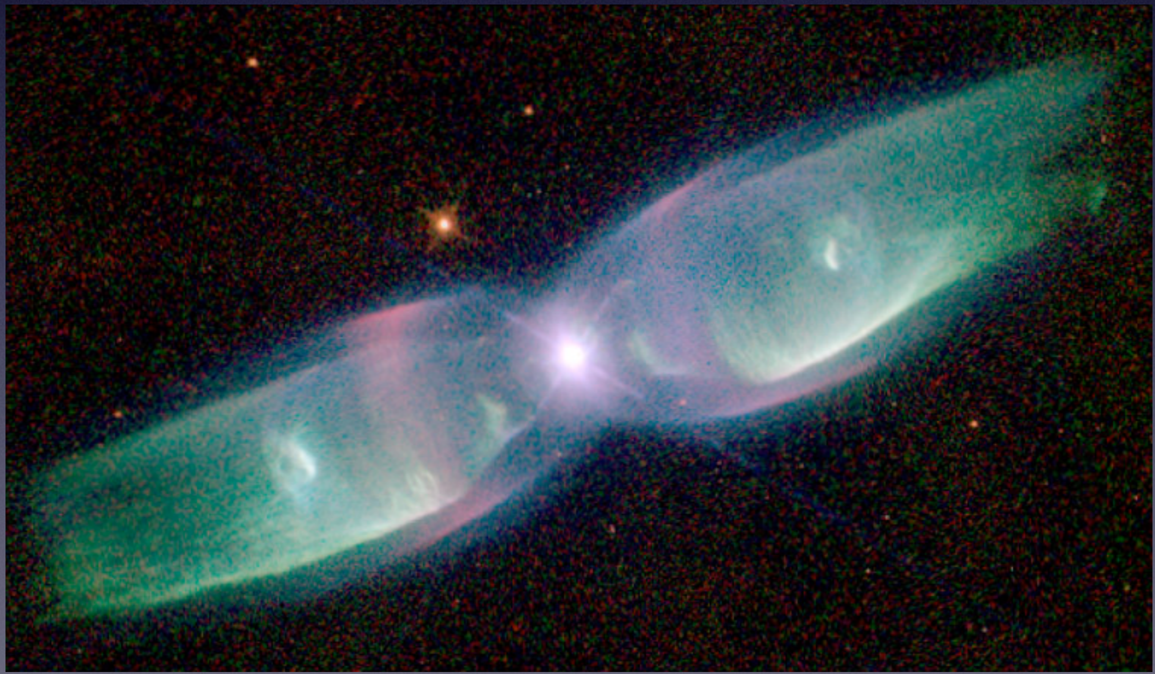

Anisoplanatism
Reference Star
Off-axis Star
Atmosphere
Residual Turbulence
Telescope
DM
WFC
WFS
© E.Marchetti / ESO / 2004





Seeing limited





Altair

Hubble

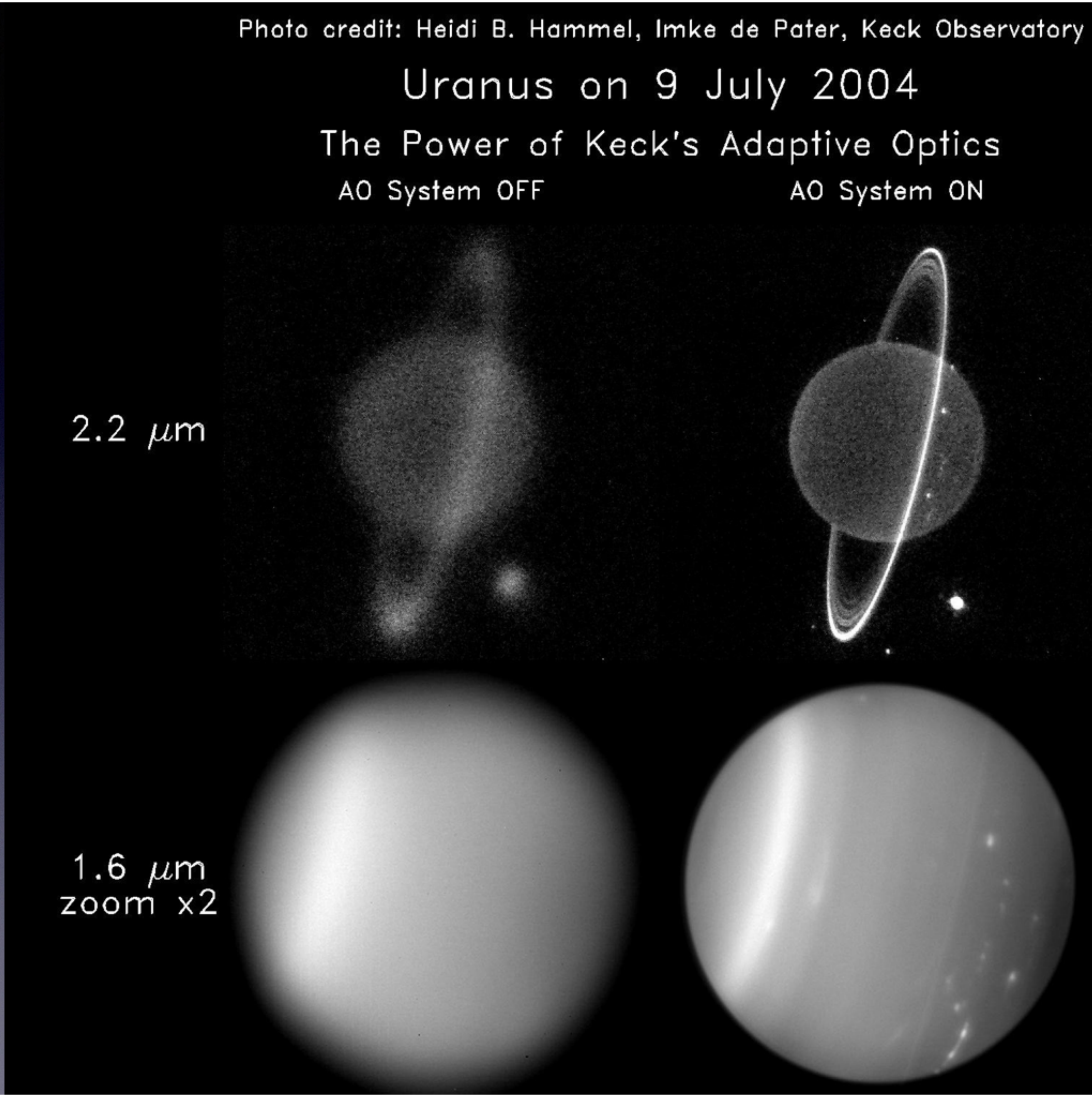
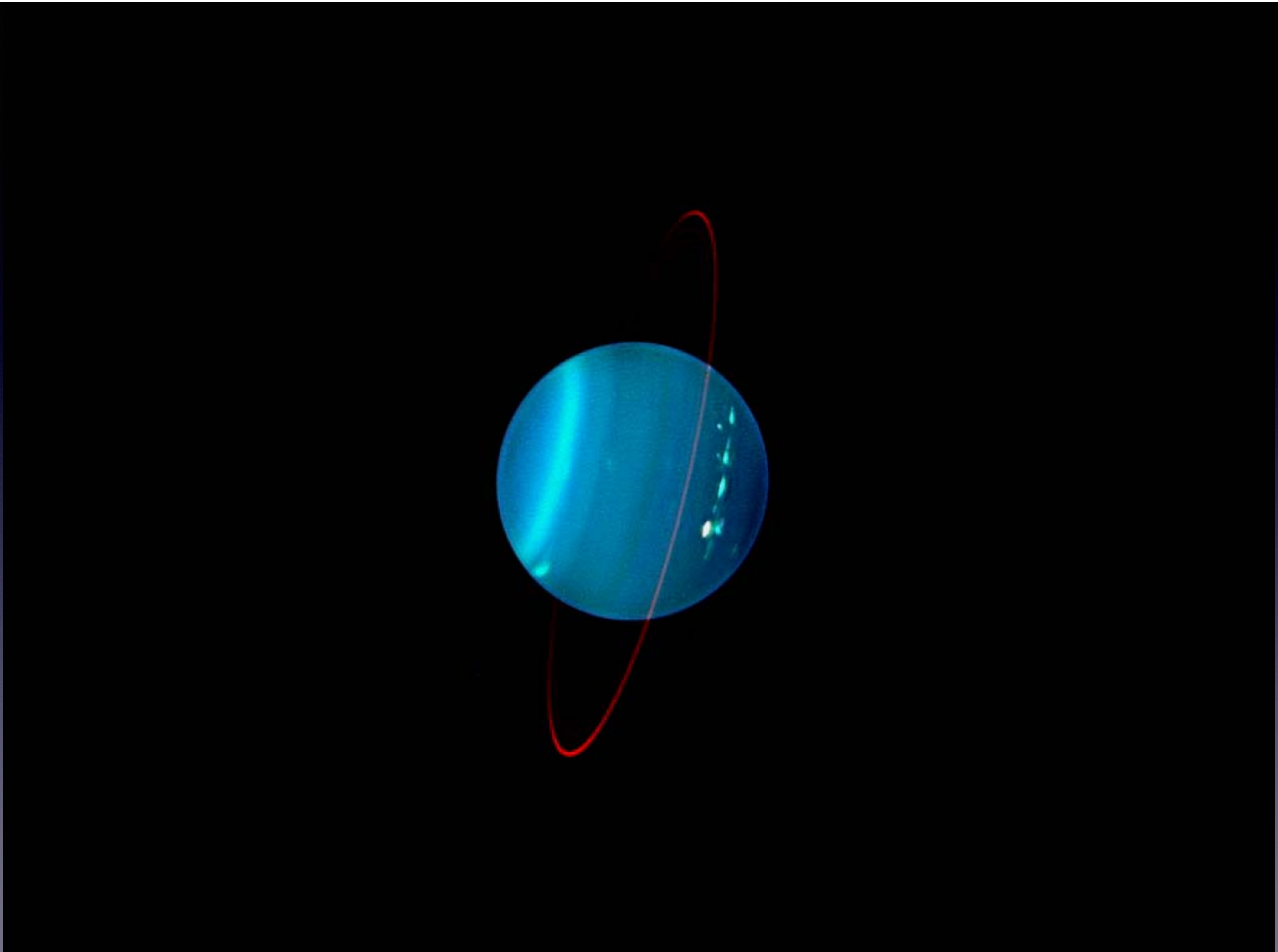
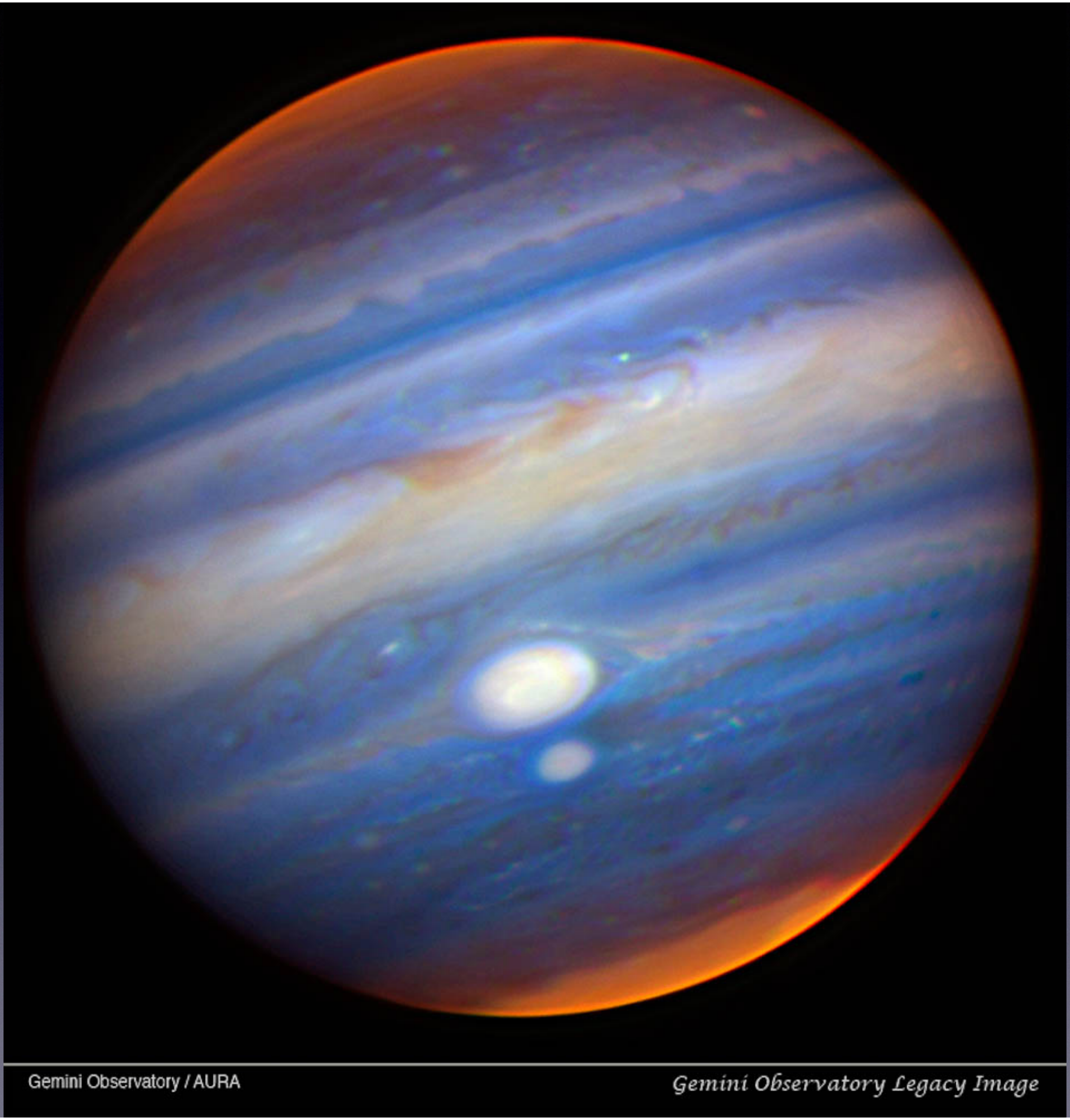
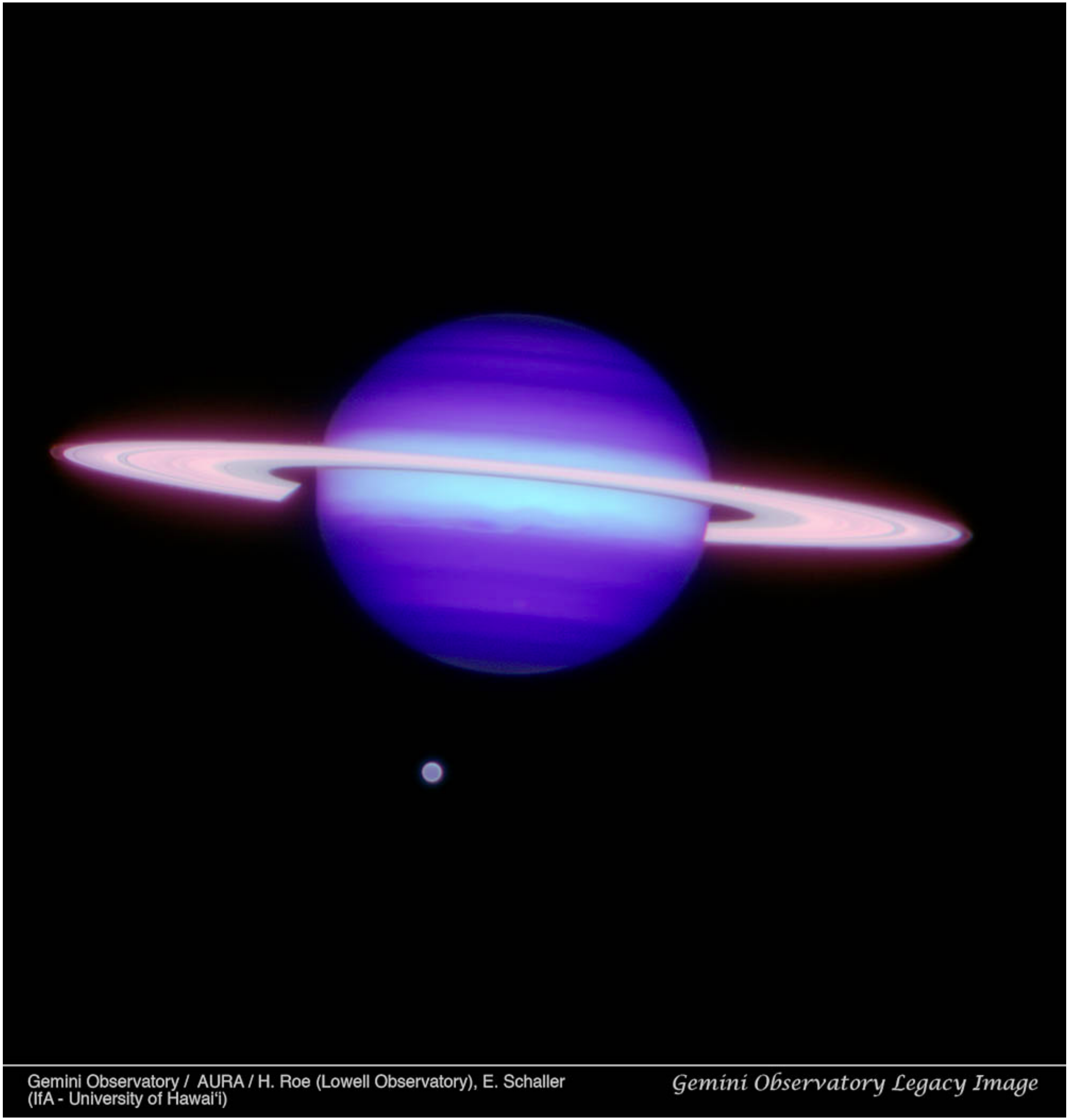
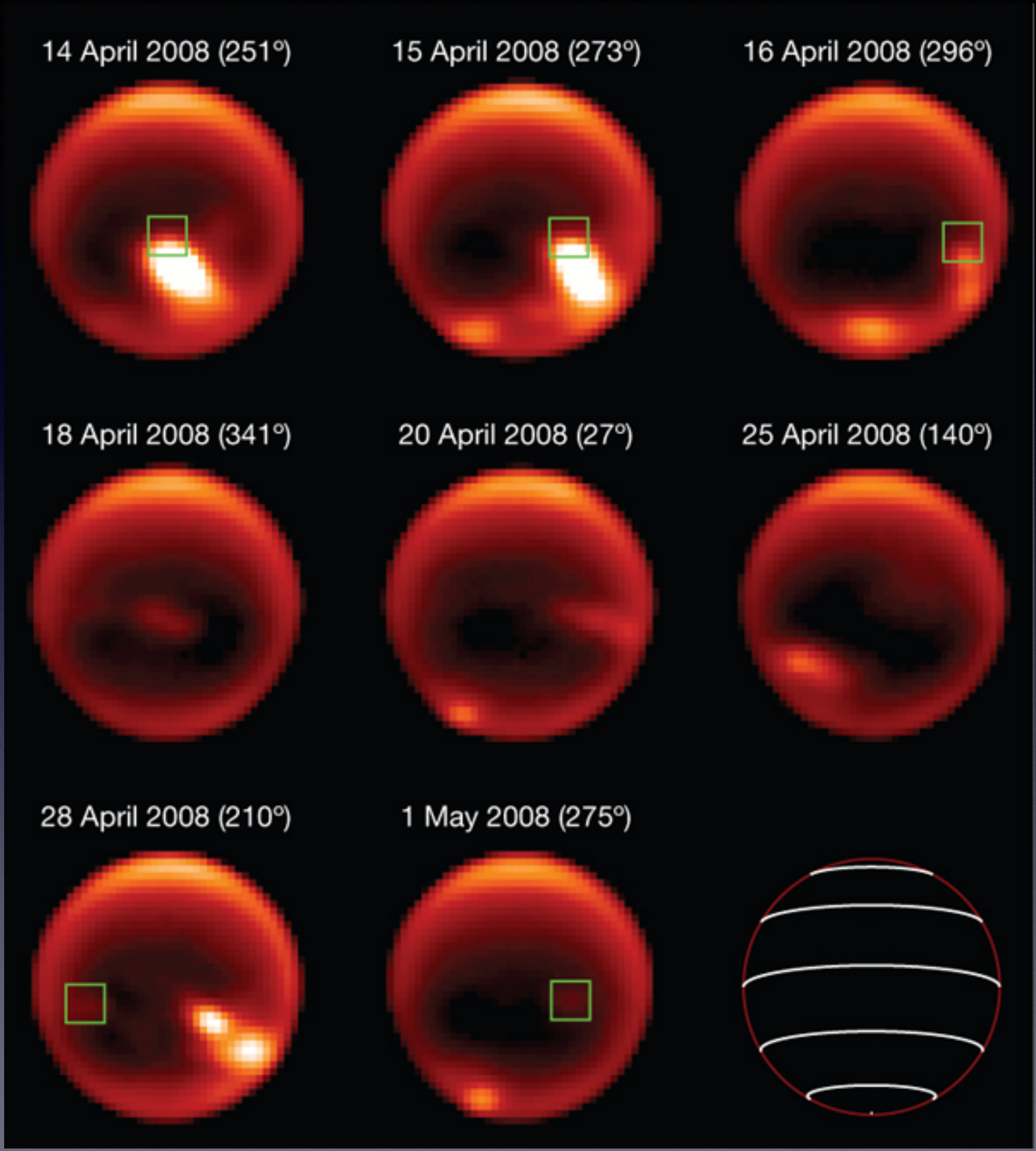


Photo credit: Heidi B. Hammel, Imke de Pater, Keck Observatory
Uranus on 9 July 2004
The Power of Keck's Adaptive Optics
AO System OFF
AO System ON
2.2 μm
1.6 μm
zoom x2




Gemini Observatory / AURA
Gemini Observatory Legacy Image


Gemini Observatory / AURA / H. Roe (Lowell Observatory), E. Schaller
(IfA - University of Hawai'i)
Gemini Observatory Legacy Image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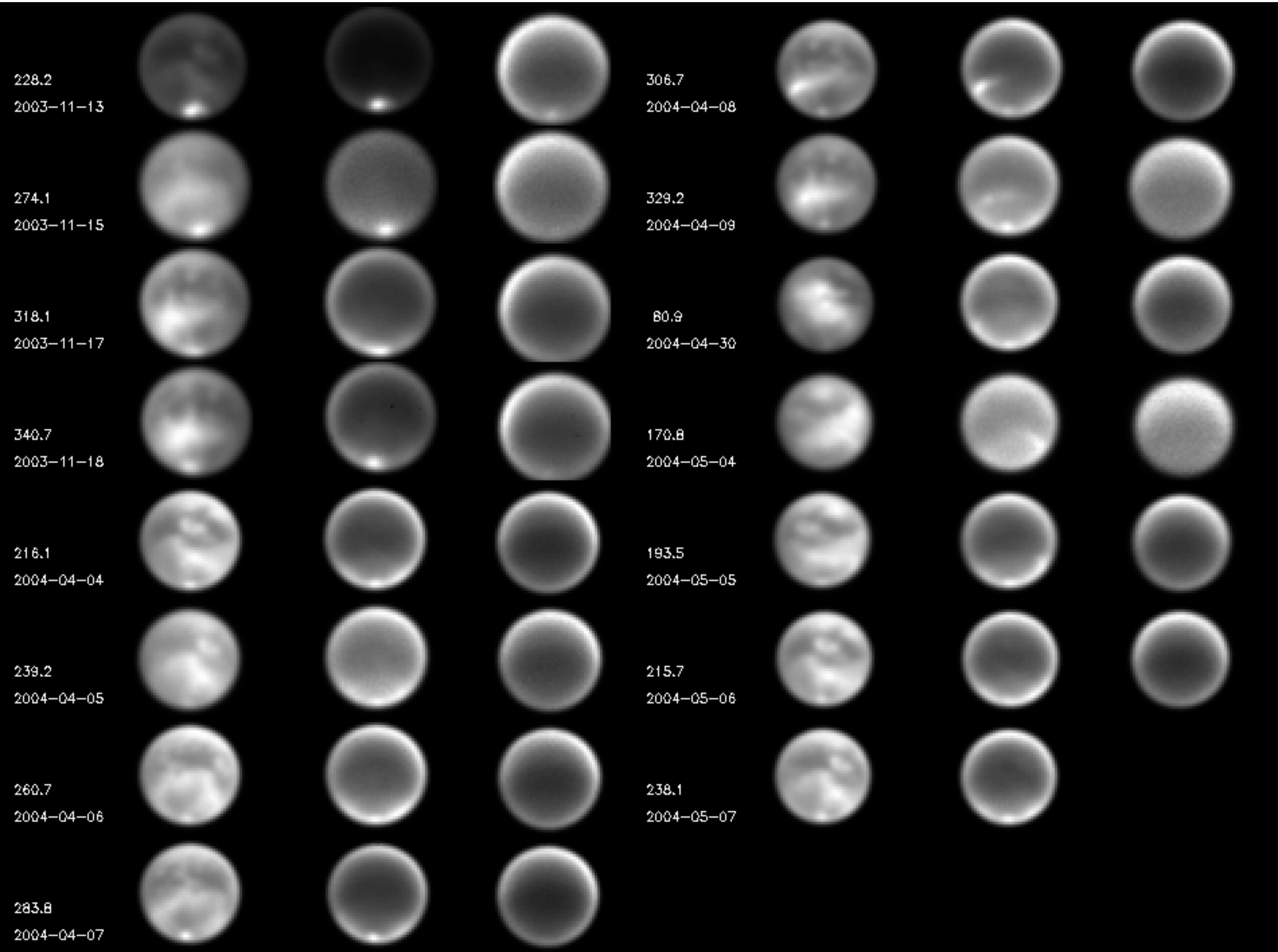
15 April 2008 (273°)
16 April 2008 (296°)
18 April 2008 (341°)
20 April 2008 (27°)
25 April 2008 (140°)
28 April 2008 (210°)
1 May 2008 (275°)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2003-11-13
274.1
2003-11-15
318.1
2003-11-17
340.7
2003-11-18
216.1
2004-04-04
239.2
2004-04-05
260.7
2004-04-06
283.8
2004-04-07
306.7
2004-04-08
329.2
2004-04-09
60.9
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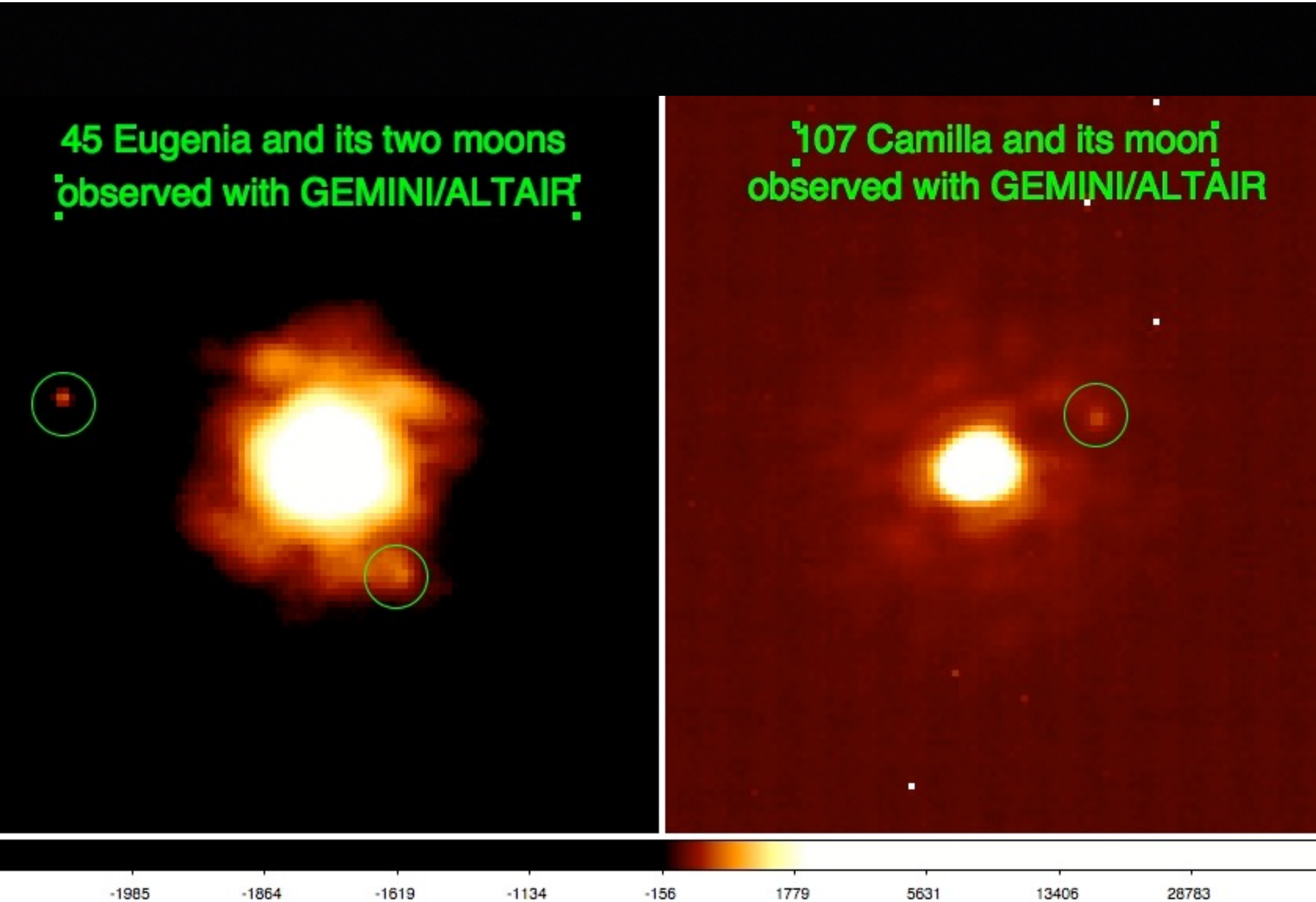
2004-05-05
215.7
2004-05-06
238.1
2004-05-07


45 Eugenia and its two moons
observed with GEMINI/ALTAIR
107 Camilla and its moon
observed with GEMINI/ALTAIR
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-1864
-1619
-1134
-156
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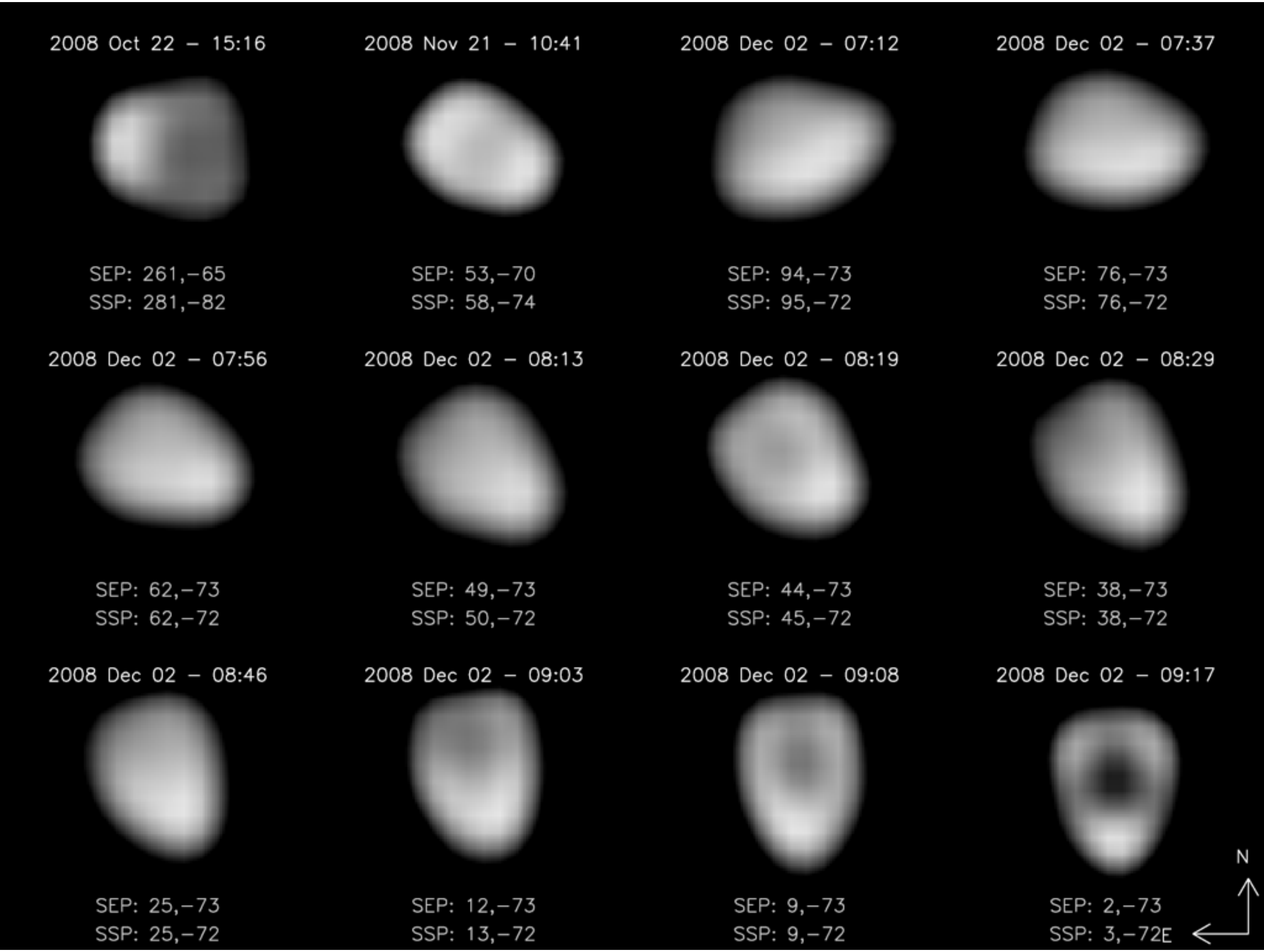
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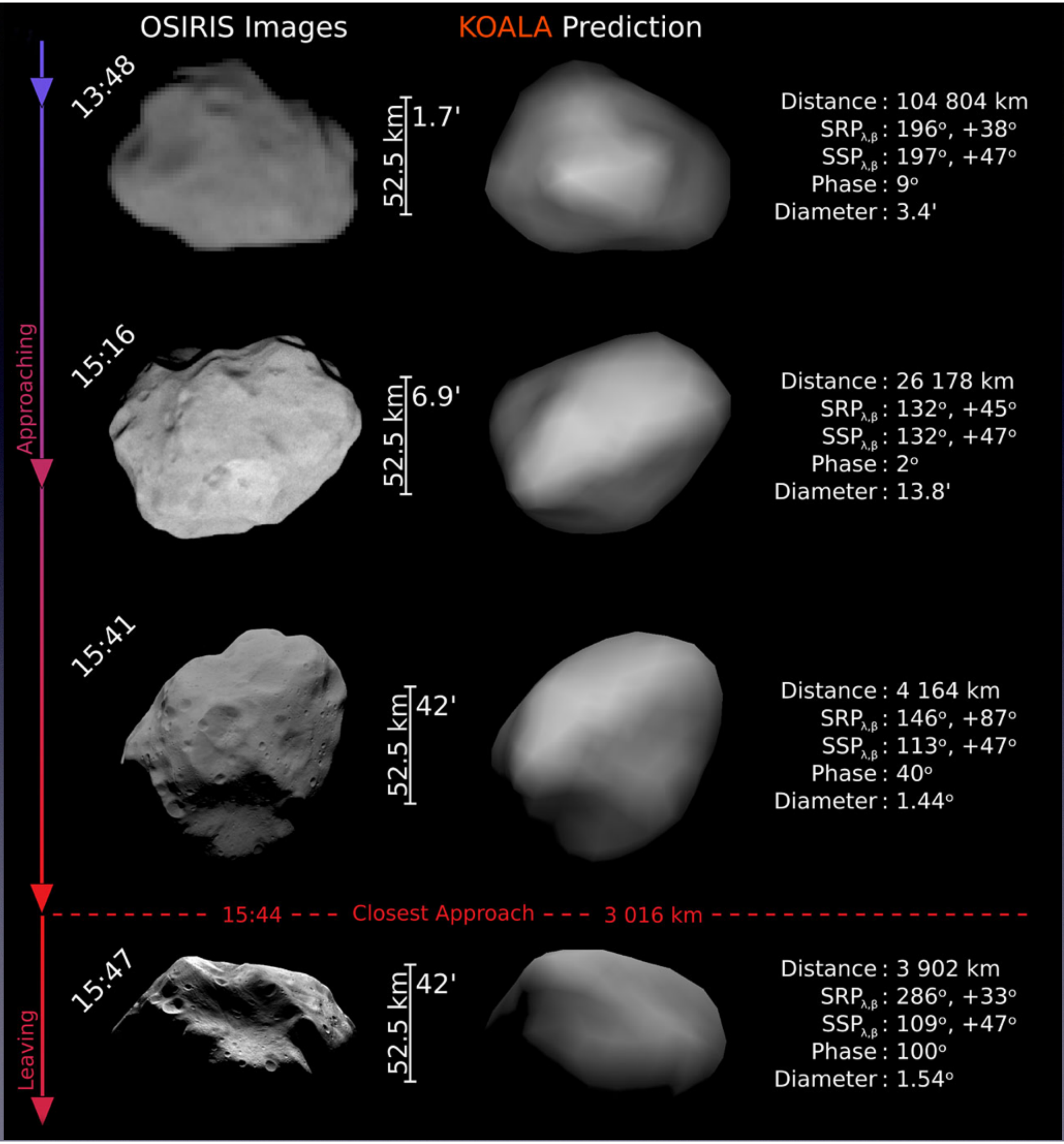
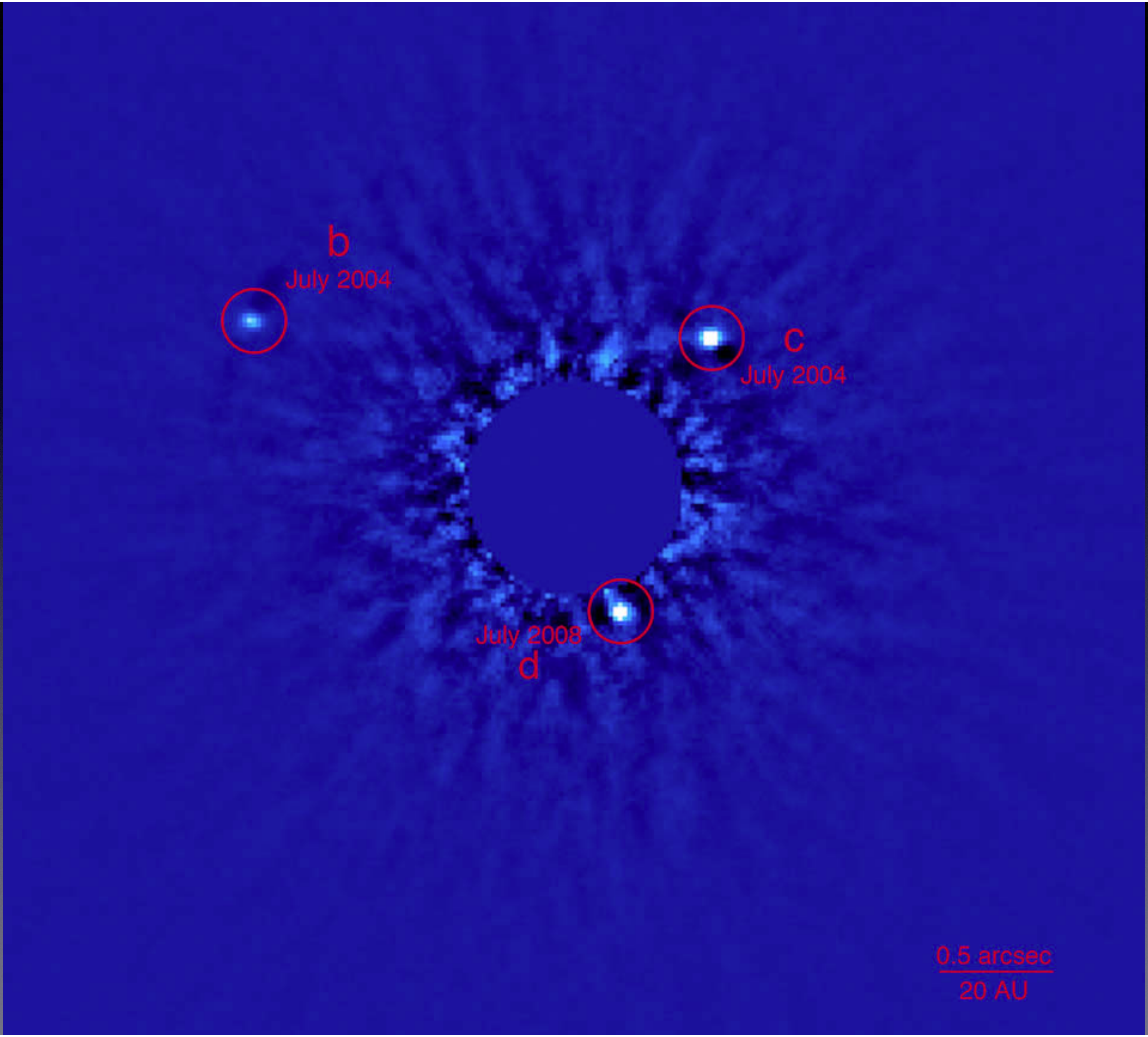
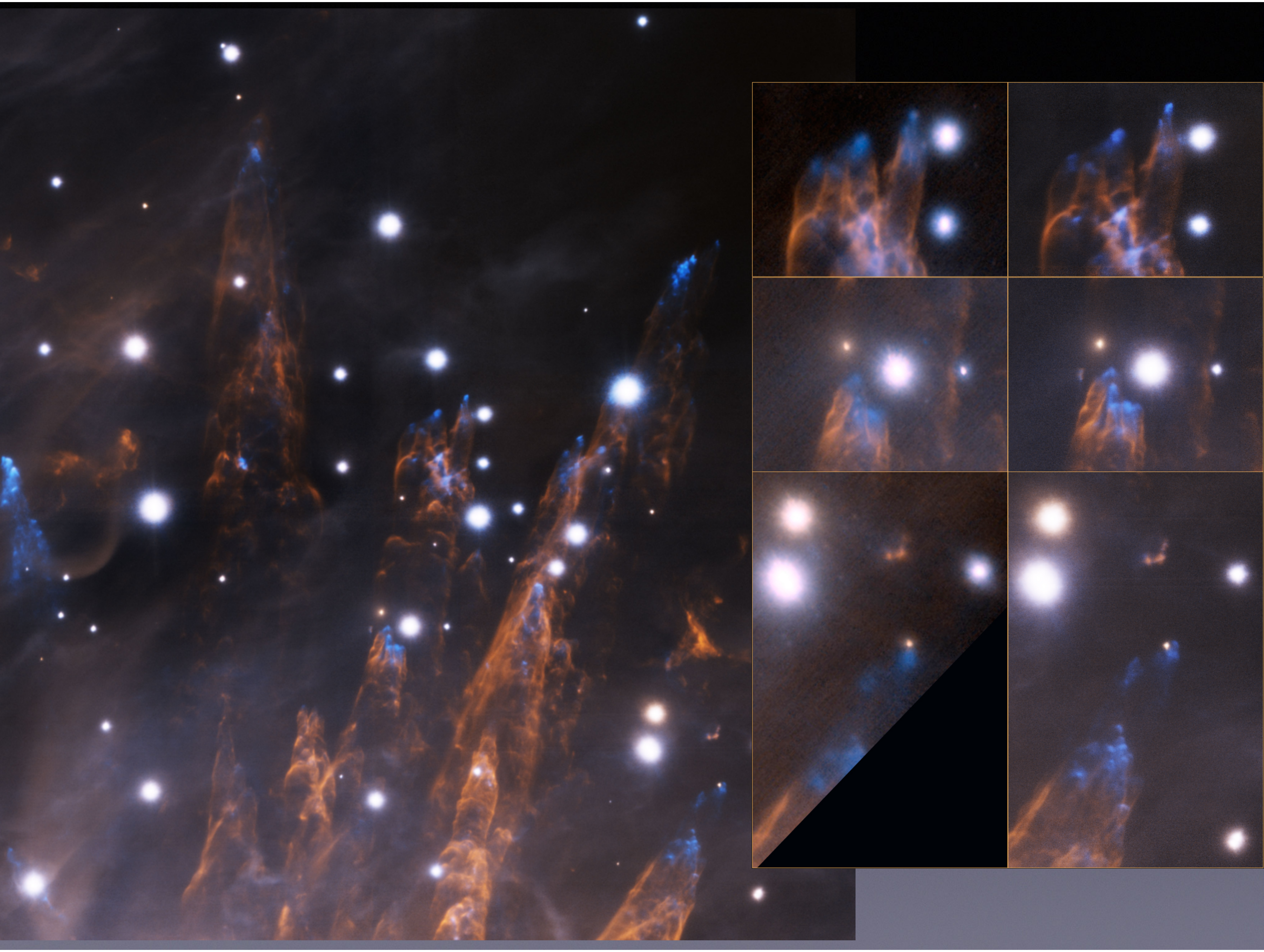
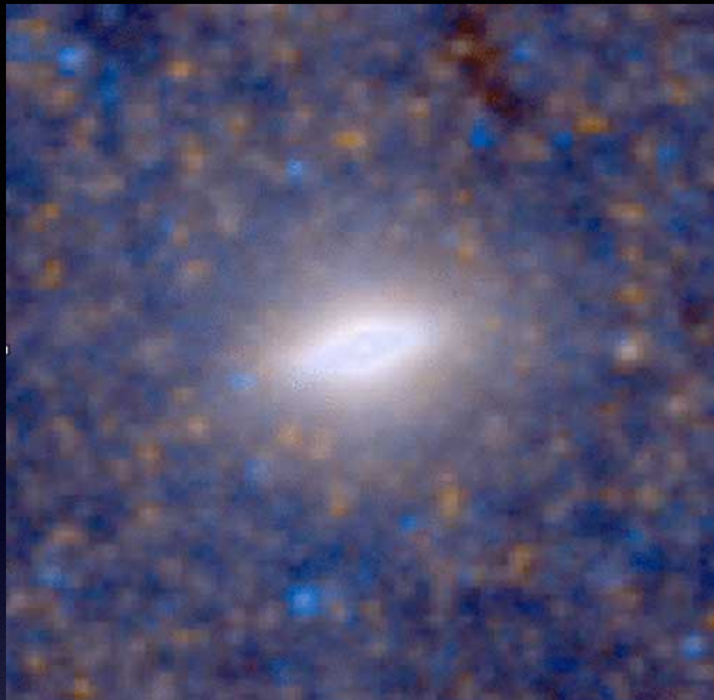
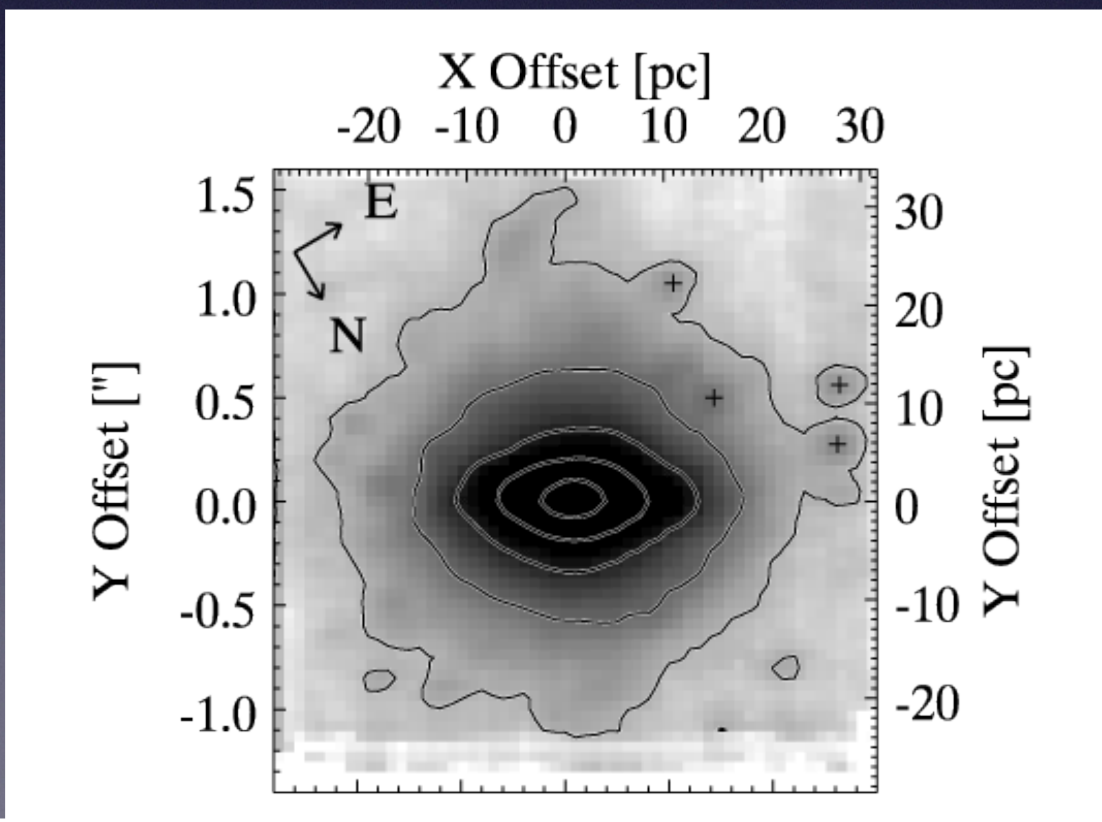
SSP: 281,–82
2008 Nov 21 – 10:41
SEP: 53,–70
SSP: 58,–74
2008 Dec 02 – 07:12
SEP: 94,–73
SSP: 95,–72
2008 Dec 02 – 07:37
SEP: 76,–73
SSP: 76,–72
2008 Dec 02 – 07:56
SEP: 62,–73
SSP: 62,–72
2008 Dec 02 – 08:13
SEP: 49,–73
SSP: 50,–72
2008 Dec 02 – 08:19
SEP: 44,–73
SSP: 45,–72
2008 Dec 02 – 08:29
SEP: 38,–73
SSP: 38,–72
2008 Dec 02 – 08:46
SEP: 25,–73
SSP: 25,–72
2008 Dec 02 – 09:03
SEP: 12,–73
SSP: 13,–72
2008 Dec 02 – 09:08
SEP: 9,–73
SSP: 9,–72
2008 Dec 02 – 09:17
SEP: 2,–73
SSP: 3,–72
N
E

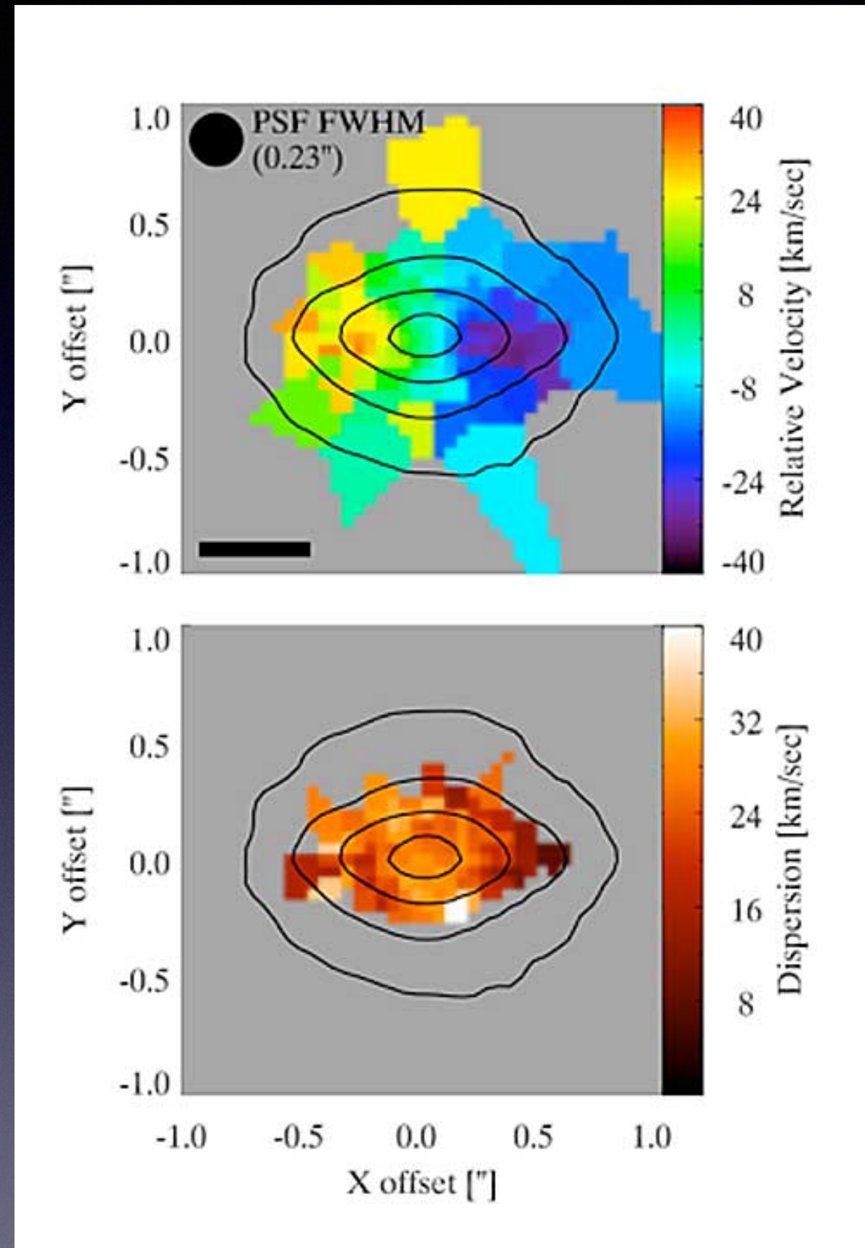

OSIRIS Images
KOALA Prediction
13:48
52.5 km
1.7'
Distance : 104 804 km
SRP$_{\lambda,\beta}$ : 196°, +38°
SSP$_{\lambda,\beta}$ : 197°, +47°
Phase : 9°
Diameter : 3.4'
15:16
52.5 km
6.9'
Distance : 26 178 km
SRP$_{\lambda,\beta}$ : 132°, +45°
SSP$_{\lambda,\beta}$ : 132°, +47°
Phase : 2°
Diameter : 13.8'
Approaching
15:41
52.5 km
42'
Distance : 4 164 km
SRP$_{\lambda,\beta}$ : 146°, +87°
SSP$_{\lambda,\beta}$ : 113°, +47°
Phase : 40°
Diameter : 1.44°
15:44 Closest Approach 3 016 km
15:47
52.5 km
42'
Distance : 3 902 km
SRP$_{\lambda,\beta}$ : 286°, +33°
SSP$_{\lambda,\beta}$ : 109°, +47°
Phase : 100°
Diameter : 1.54°
Leaving


b
July 2004
c
July 2004
July 2008
d
0.5 arcsec
20 AU






X Offset [pc]
-20 -10 0 10 20 30
1.5
1.0
0.5
0.0
-0.5
-1.0
Y Offset ["]
30
20
10
0
-10
-20
Y Offset [pc]
E
N


PSF FWHM
(0.23")
1.0
0.5
0.0
-0.5
-1.0
Y offset ["]
40
24
8
-8
-24
-40
Relative Velocity [km/sec]
1.0
0.5
0.0
-0.5
-1.0
Y offset ["]
40
32
24
16
8
Dispersion [km/sec]
-1.0 -0.5 0.0 0.5 1.0
X offset ["]

# Adaptive Optics

- Atmospheric Turbulence
- Sensing the wave front
- Correcting the wave front
- Laser Guide Stars
- Other types of AO systems

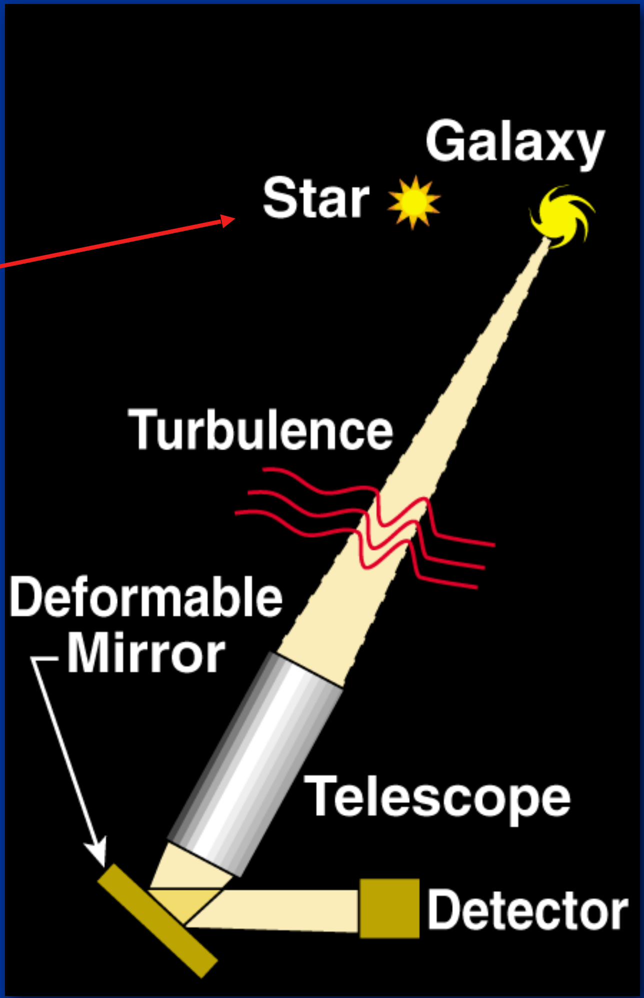
# Laser guide stars: Main points

- Laser guide stars are needed because there aren't enough bright natural guide stars in the sky
  - Hence YOUR favorite galaxy probably won't have a bright enough natural guide star nearby
- Solution: make your own guide star using lasers
  - Nothing special about coherent light - could use a flashlight hanging from a "giant high-altitude helicopter"
  - Size on sky has to be ≲ diffraction limit of a WFS sub-aperture
- Laser guide stars have pluses and minuses:
  - Pluses: can put them anywhere, can be bright
  - Minuses: NGS give better AO performance than LGS even when both are working perfectly. High-powered lasers are tricky to build and work with. Laser safety is added complication.


Credit: Claire E. Max, UCSC

# *If there's no close-by "real" star, create one with a laser*

- Use a laser beam to create artificial "star" at altitude of 100 km in atmosphere




Credit: Claire E. Max, UCSC

# *Laser guide stars are operating at Lick, Keck, Gemini N & S, VLT, Subaru, …*

**Four lasers on Mauna Kea: Keck 1 and 2, Gemini, Subaru telescopes**

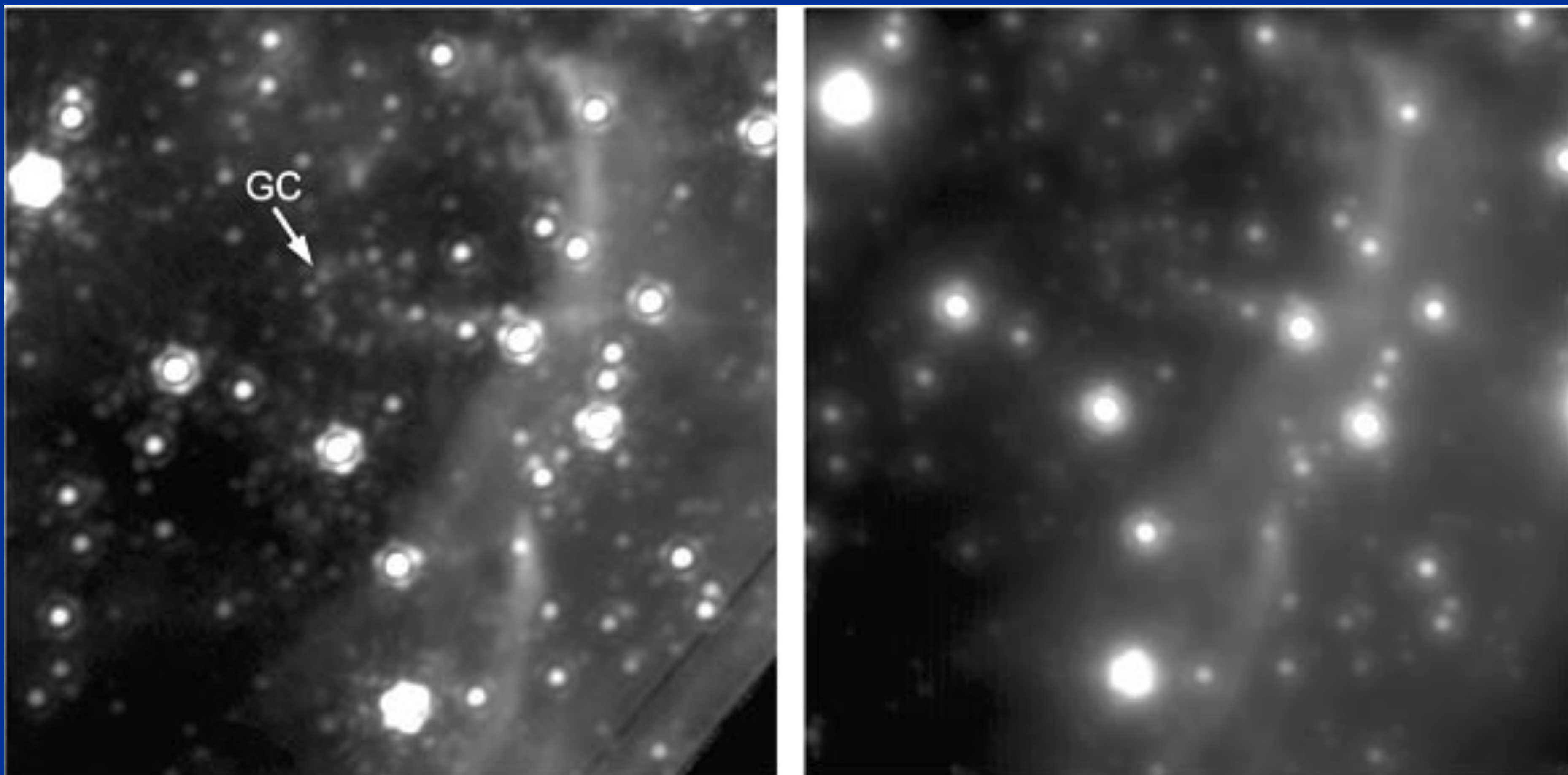


**Credit: Claire E. Max, UCSC** 

https://vimeo.com/75542539

# Galactic Center with Keck laser guide star (GC is location of supermassive black hole)

Keck laser guide star AO | Best natural guide star AO



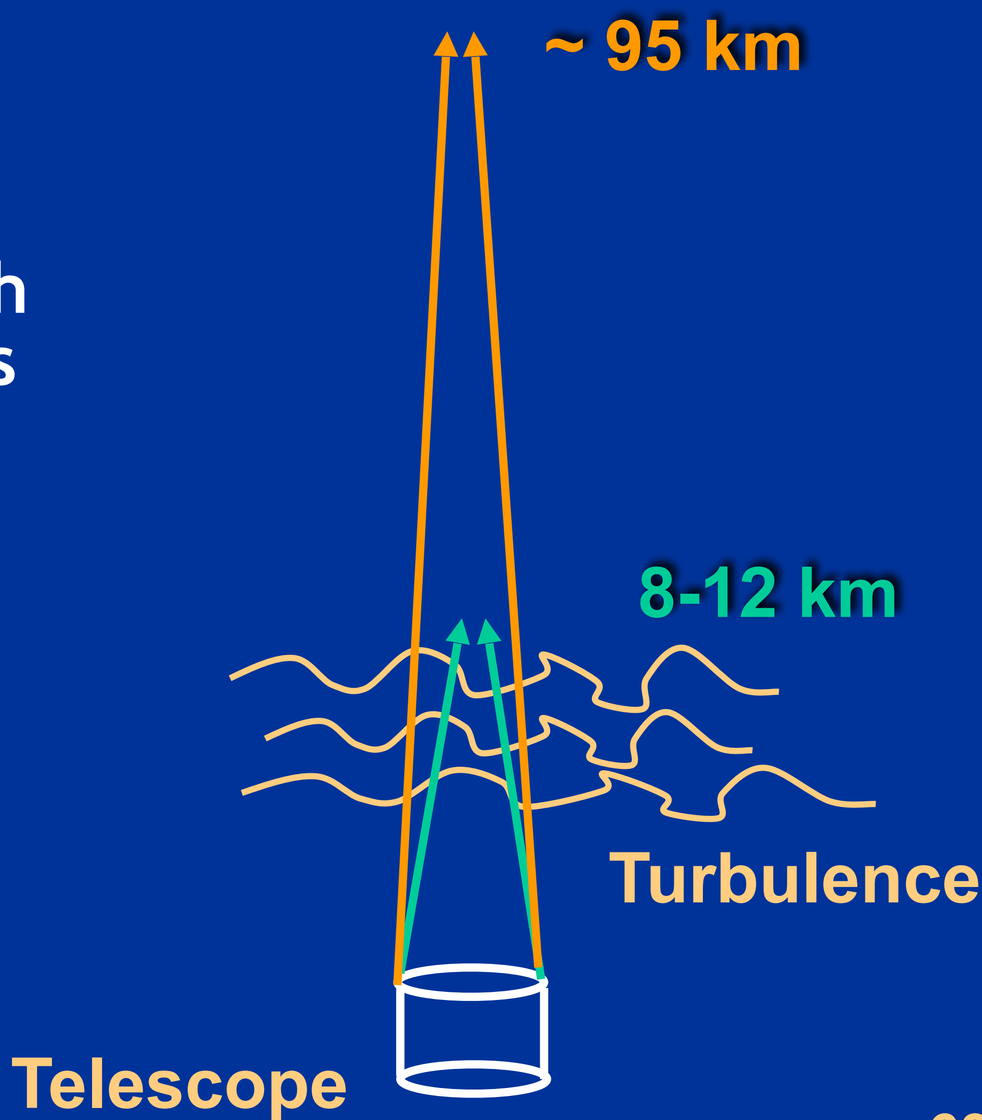

Source: UCLA Galactic Center group



Credit: Claire E. Max, UCSC

# *Two types of laser guide stars in use today: "Rayleigh" and "Sodium"*

- **Sodium guide stars:** excite atoms in "sodium layer" at altitude of ~ 95 km
- **Rayleigh guide stars:** Rayleigh scattering from air molecules sends light back into telescope, h ~ 10 km
- Higher altitude of sodium layer is closer to sampling the same turbulence that a star from "infinity" passes through




Credit: Claire E. Max, UCSC

# *Reasons why laser guide stars can't do as well as bright natural guide stars*

1) Laser light is spread out by turbulence on the way up.
   - Spot size is finite (0.5 - 2 arc sec)
   - Can increase measurement error of wavefront sensor
     » Harder to find centroid if spot is larger

2) For Rayleigh guide stars, some turbulence is above altitude where light is scattered back to telescope.
   - Hence it can't be measured.

3) For both kinds of guide stars, light coming back to telescope is spherical wave, but light from "real" stars is plane wave
   - Some turbulence around edges of the pupil isn't sampled well



Credit: Claire E. Max, UCSC

# *Laser beacon geometry causes measurement errors*

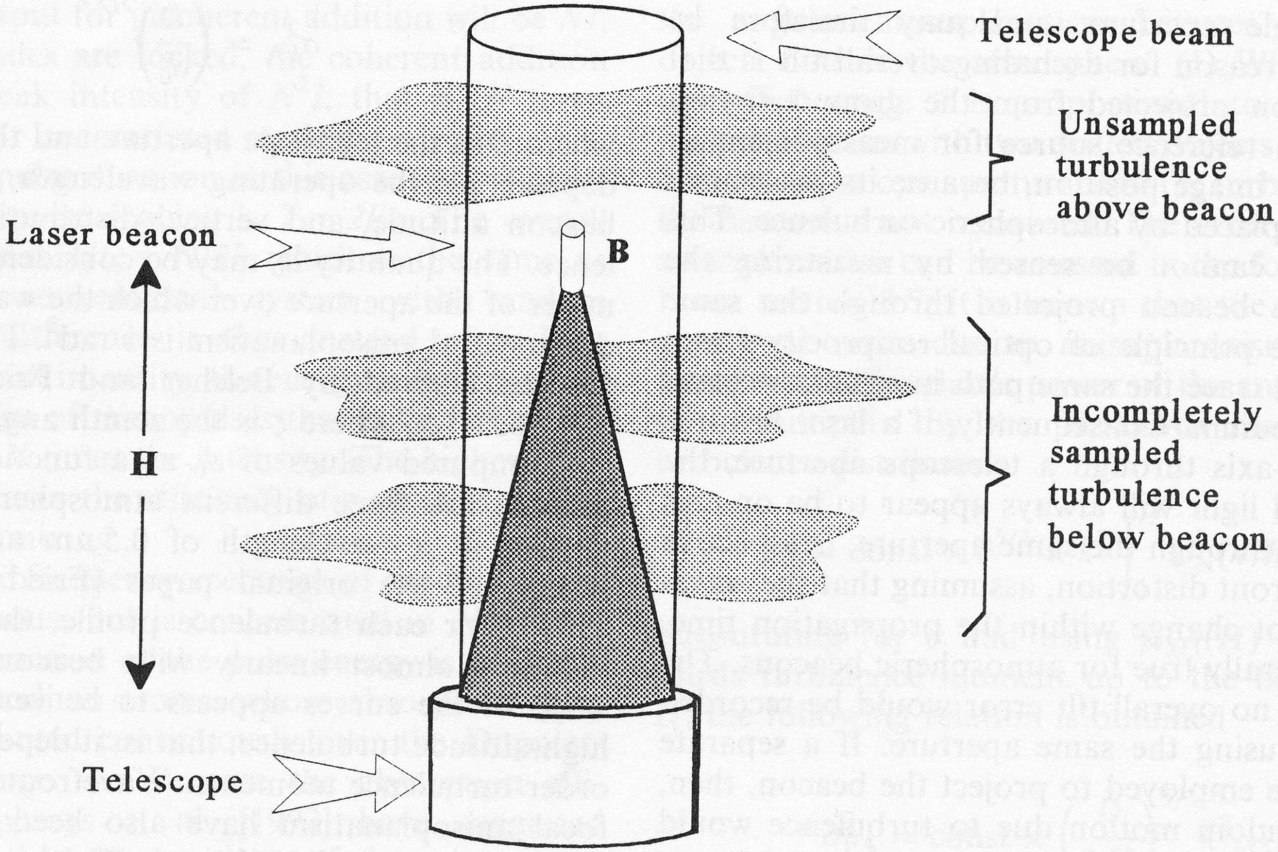



Figure 7.14 Laser beacon measurement errors.

Credit: Hardy

# *If we can only use guide stars closer than ~ 40 arc sec, sky coverage is low!*

- High-order Shack-Hartmann AO systems typically need guide stars brighter than magnitude V ~ 13.5 [V band: central wavelength ~ 0.54 $\mu$m]
- Surface density of these stars on the sky is $\Sigma \sim 10^{-5} / (\text{arc sec})^2$
- So probability *P* of finding bright enough guide star w/in radius of 40 arc sec of an arbitrary place in the sky is

$$P = \Sigma \, \pi \, (40)^2 = 10^{-5} \, \pi \, (40)^2 = 0.05$$

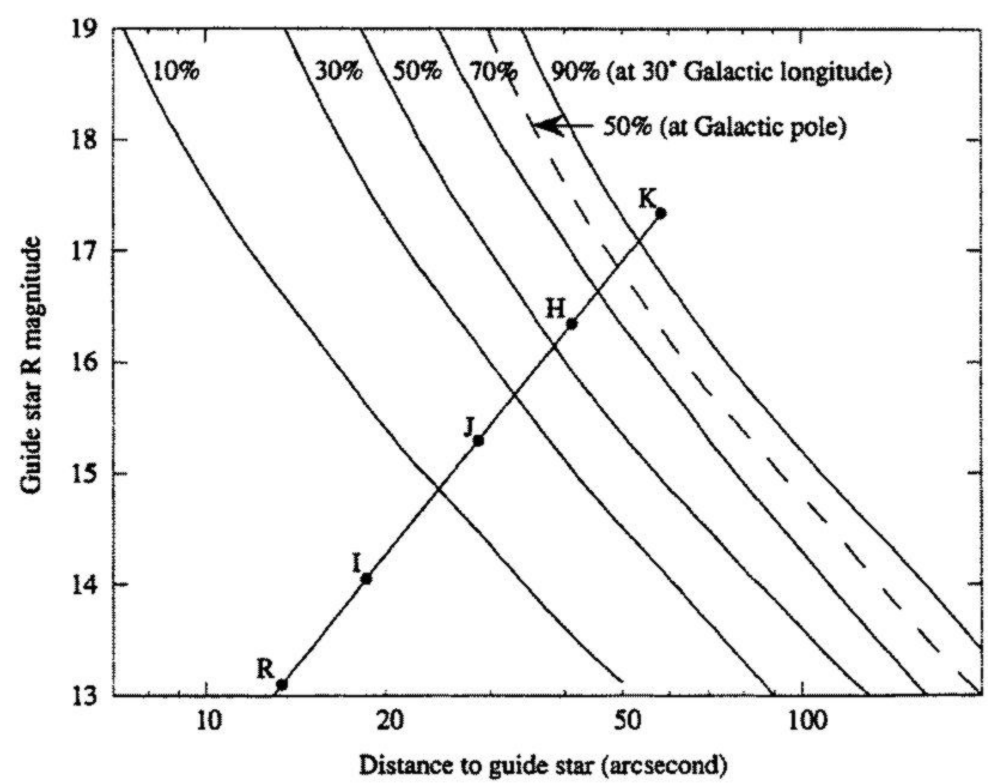
- Magnitude V ~ 13.5 stars only have 5% sky coverage!


Credit: Claire E. Max, UCSC

# *Sky coverage for curvature sensing AO system*

- Can use fainter guide stars, sometimes at expense of lower Strehl ratio
- Graph trades off guide star brightness with distance from guide star

| Image spectral band | R | I | J | H | K |
|---|---|---|---|---|---|
| Wavelength (for imaging) | 0.65 | 0.85 | 1.22 | 1.65 | 2.2 |
| Maximum guide star mag (at 0.63 μm) | 13.1 | 14.0 | 15.2 | 16.3 | 17.3 |
| Maximum angular distance (arcsec) | 13.4 | 18.6 | 28.6 | 41.1 | 58.1 |





Credit: Claire E. Max, UCSC

# *Solution: make your own guide star using a laser beam*

- Point the laser beam directly at YOUR favorite astronomical target
- Use scattering of laser light by the atmosphere to create an "artificial" guide star
  - Sometimes called "synthetic beacon" or "artificial beacon"
- What physical mechanism causes the laser light to scatter back down into your telescope's wavefront sensor?


Credit: Claire E. Max, UCSC

# *Scattering: 2 different physical processes*

- Rayleigh Scattering (Rayleigh beacon)
  - Elastic scattering from atoms or molecules in atmosphere. Works for broadband light, no change in frequency
- Resonance Scattering (Sodium Beacon)
  - Line radiation is absorbed and emitted with no change in frequency.


Credit: Claire E. Max, UCSC

# *Rayleigh laser guide stars*

- LBT ARGOS laser guide star


- Starfire Optical Range, NM. Quite a few years ago.

Robo-AO UV laser



Credit: Claire E. Max, UCSC

# *Sodium Resonance Fluorescence*

- Resonance scattering occurs when incident laser is tuned to a specific atomic transition.
- Absorbed photon raises atom to excited state.  Atom emits photon of same wavelength via spontaneous or stimulated emission, returning to original lower state.
- Large absorption and scattering cross-sections.
- Layer in mesosphere ( $h \sim 95$ km, $\Delta h \sim 10$ km) containing alkali metals, sodium ($10^3$ - $10^4$ atoms/cm$^3$), potassium, calcium
- Strongest laser return is from $D_2$ line of Na at 589 nm.


Credit: Claire E. Max, UCSC

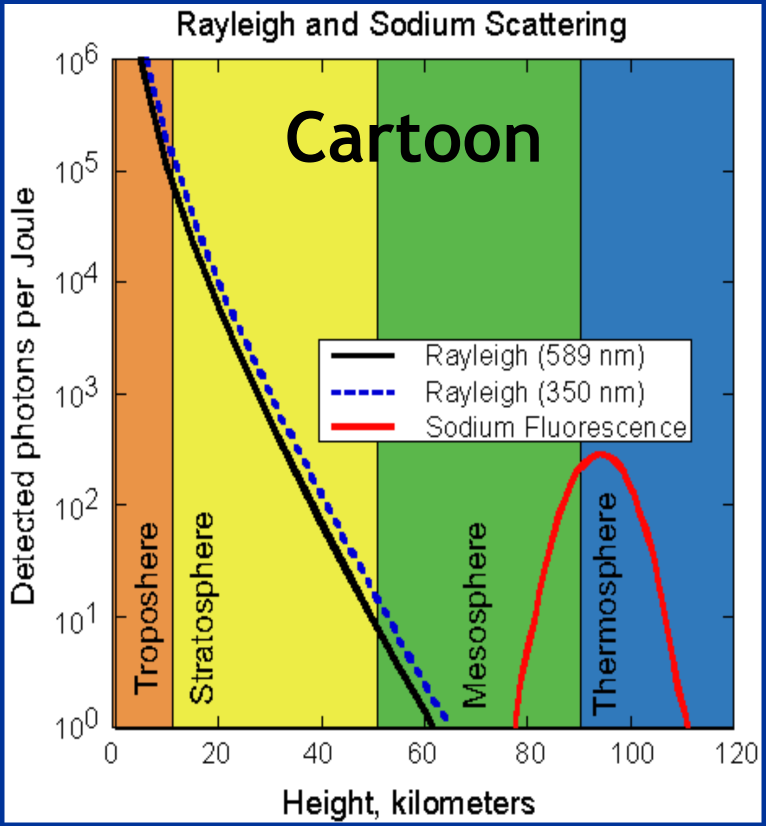
# *Rayleigh scattering vs. sodium resonance fluorescence*

- Atmosphere has ~ exponential density profile:

$$-\nabla(nkT) = nMg \Rightarrow n(z) = n_o \exp-\left(\frac{Mg\,z}{kT}\right)$$

- M = molecular mass, n = no. density, T = temperature, k = Planck's constant, g = gravitational acceleration

- Rayleigh scattering dominates over sodium fluorescence scattering below h = 75 km.






Credit: Claire E. Max, UCSC

# LZT LIDAR

Home | Overview | Science | Papers | Archive

## Welcome

The lidar facility of the Large Zenith Telescope is used to study the upper atmopshere, between 74 and 120 km above sea level. In this region, meteors that enter the atmopshere deposit iron, potassium, sodium and oher atoms. The LZT lidar facility is designed to study the density and distribution of sodium atoms, for astronomy and atmospheric physics. With a resolution of 4.8 metres, it is the most powerful facility of its kind.

| more

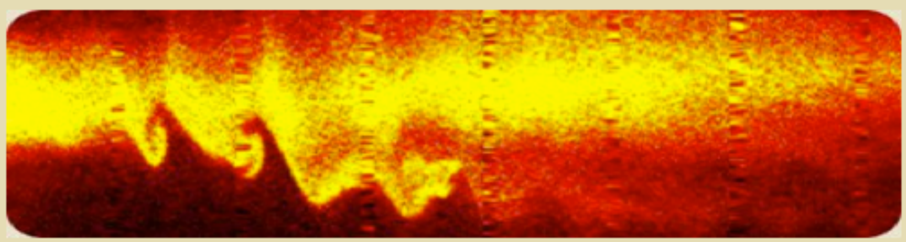
## What is Lidar?

Lidar is similar to radar, but employs light. Pulses of light, produced by a powerful laser, are fired upward throught the atmopshere. These pulses excite sodium atoms in the mesosphere, about 90 kilometers above the Earth's surface. The excited sodium atoms re-emit the photons that they absorb, some of which propagate downward towards a receiving telescope. Each photon collected by the telescope is measured, and its time of arrival is recorded. From the time difference between the reception of the photon, and the firing of the laser pulse, the distance to the sodium atom can be determined. In this way, it is possible to determine the number of sodium atoms as a function of altitude.

| more

## Recent Results

This image shows sodium density above the facility as a function of altitude (75 to 105 km) and time (horizontal direction, covering about 5 hours) on the night of August 5, 2008.



Here we see a layer of sodium atoms becoming unstable and developing vortices. The vertical extent is 5 km and the elapsed time is 20 min.

| more

The LZT lidar facility is the Ph.D. project of UBC graduate student Thomas Pfrommer.



Credit: Claire E. Max, UCSC

# *Toptica fiber laser (ESO, Keck 2)*

Fiber laser

Electronics and cooling



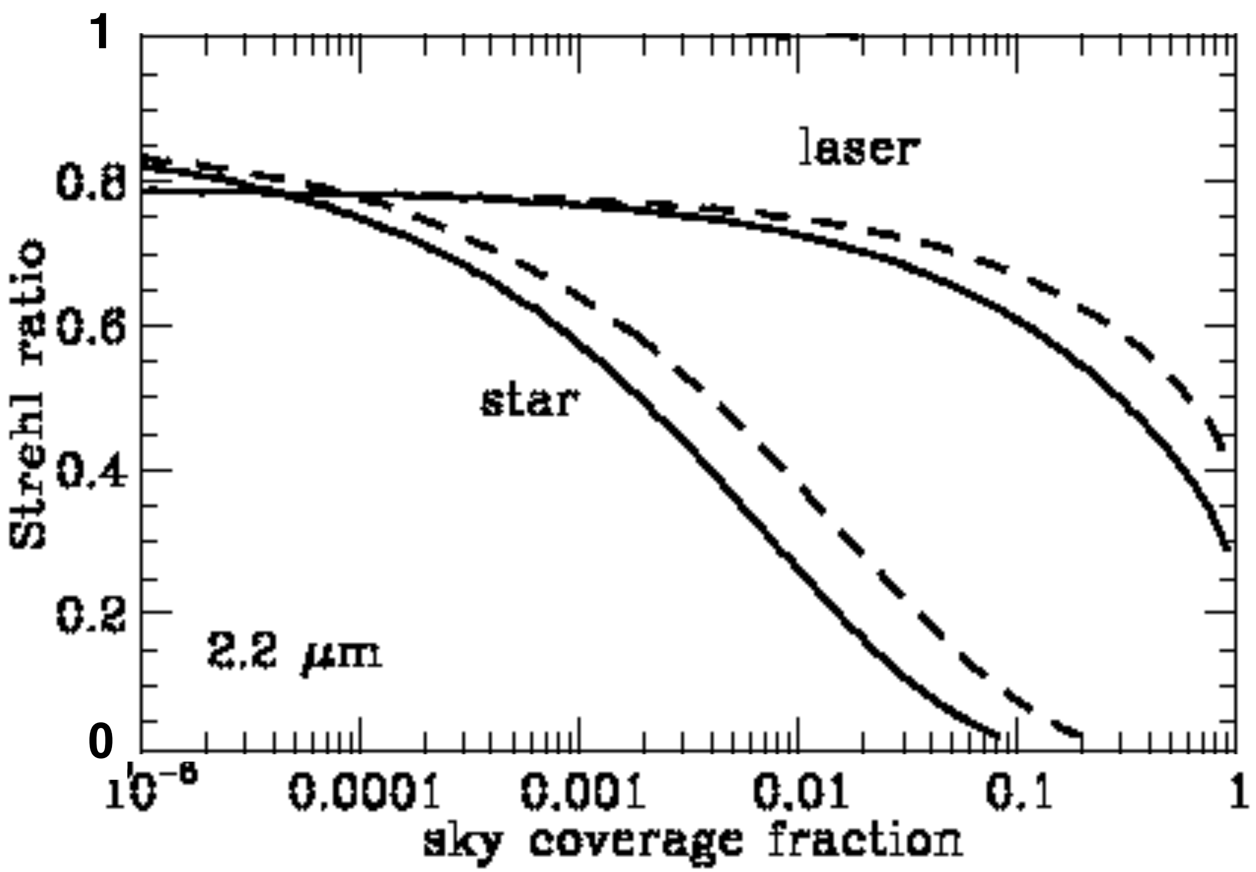
Credit: Claire E. Max, UCSC

# Advantages of fiber lasers

- Very compact
- Commercial parts from telecommunications industry
- Efficient:
  - Pump with laser diodes - high efficiency
  - Pump fiber all along its length - excellent surface to volume ratio
- Two types of fiber lasers have been demonstrated at the required power levels at 589 nm (Toptica in Europe, Jay Dawson at LLNL)

# *Sky coverage is determined by distribution of (faint) tip-tilt stars*

- Keck: >18th magnitude




From Keck AO book

— Galactic latitude = 90°
.....Galactic latitude = 30°

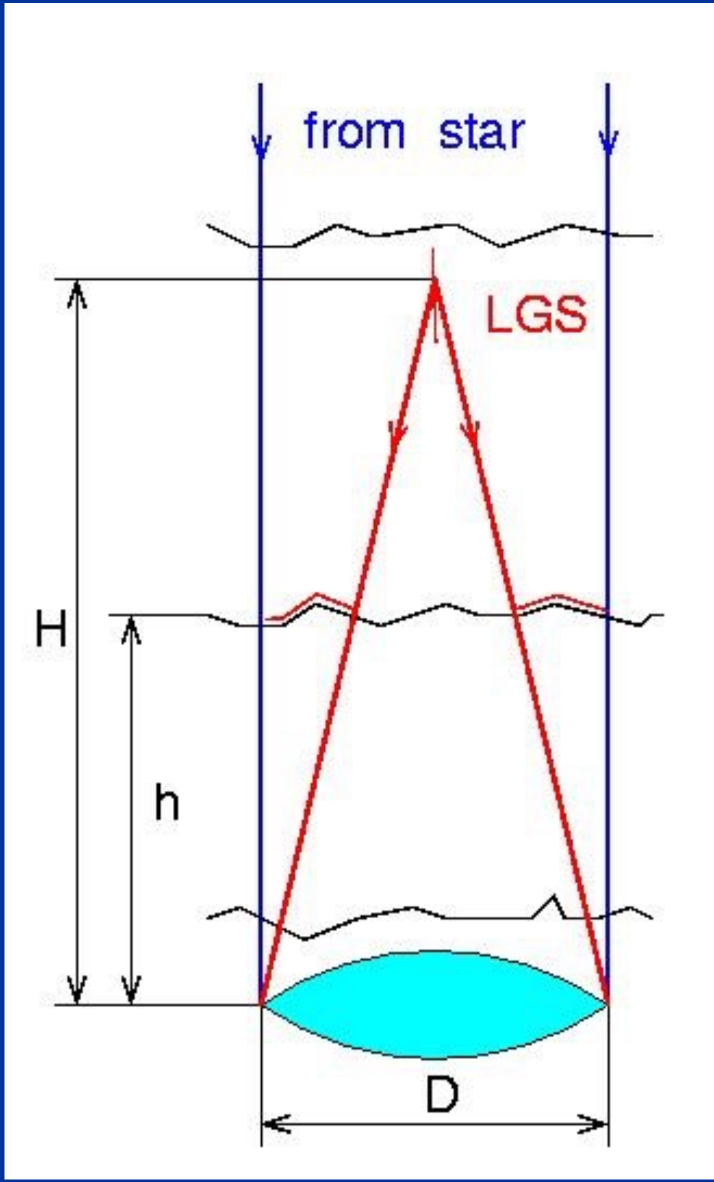
271 degrees of freedom
5 W cw laser



Credit: Claire E. Max, UCSC

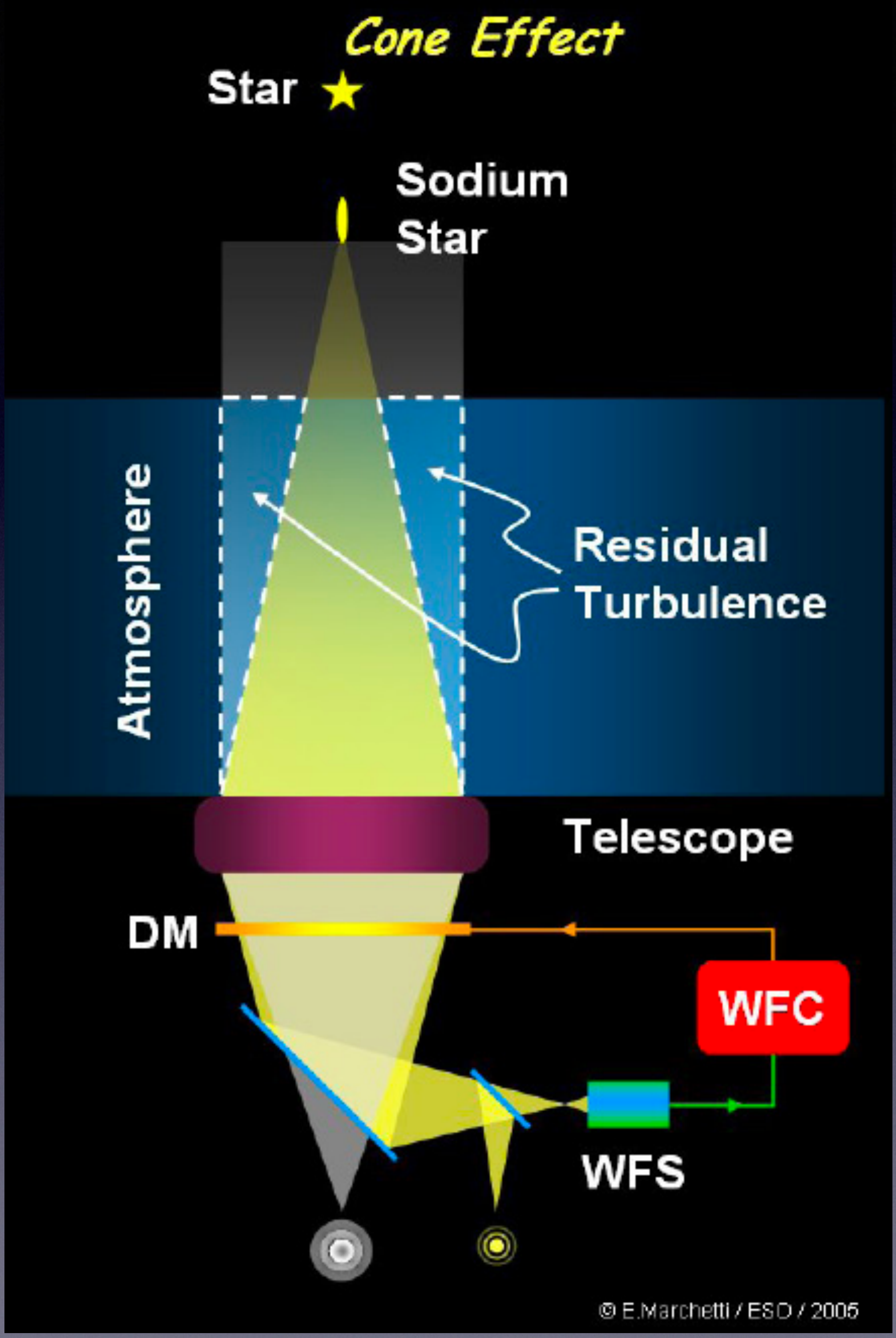
# *"Cone effect" or "focal anisoplanatism" for laser guide stars*

- Two contributions:
  - Unsensed turbulence above height of guide star
  - Geometrical effect of unsampled turbulence at edge of pupil




from A. Tokovinin

Credit: Claire E. Max, UCSC



Cone Effect
Star
Sodium
Star
Atmosphere
Residual
Turbulence
Telescope
DM
WFC
WFS
© E.Marchetti / ESO / 2005

# Adaptive Optics

- Atmospheric Turbulence
- Sensing the wave front
- Correcting the wave front
- Laser Guide Stars
- Other types of AO systems

| AO Flavor | Capabilities | Science | Instrument |
|---|---|---|---|
| Extreme | Very High Contrast, Tiny Field | Exoplanets | GPI |
| Multiconjugate | Moderate Contrast, Wide Field | Galactic, Extragalactic | GeMS |
| Laser Single Conjugate | Moderate Contrast, Moderate Field | All | Altair |
| Multi Object | High Contrast, Multiple Locations | Galactic, Extragalactic | RAVEN |
| Ground Layer | Low Contrast, Widest Field, All Sky | All | ARGOS |

# Ground based Instruments: Exoplanet direct imaging instruments

GPI

Macintosh et al, 14

SPHERE

Beuzit et al, 14

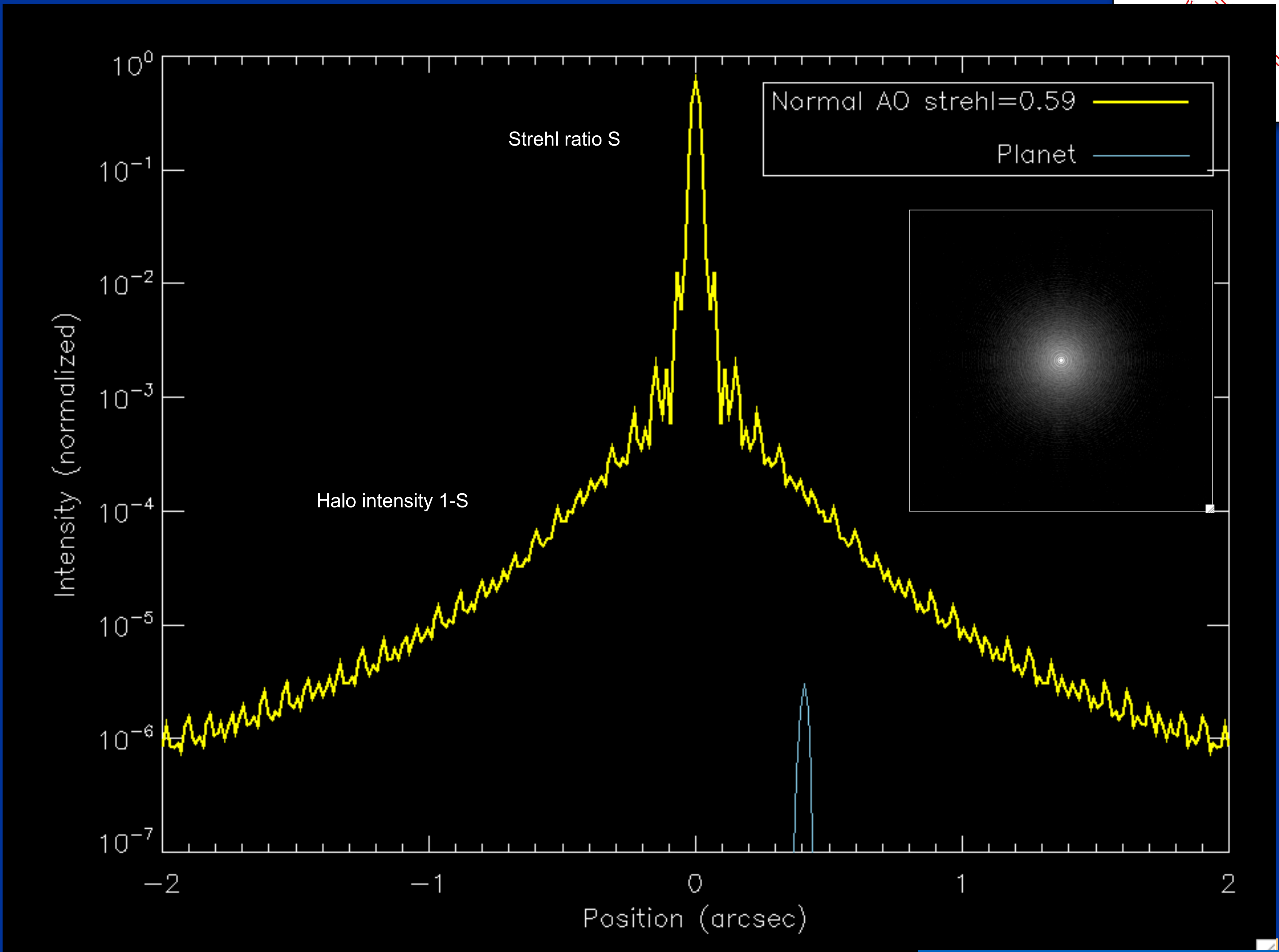
P1640

Hinkley et al, 08

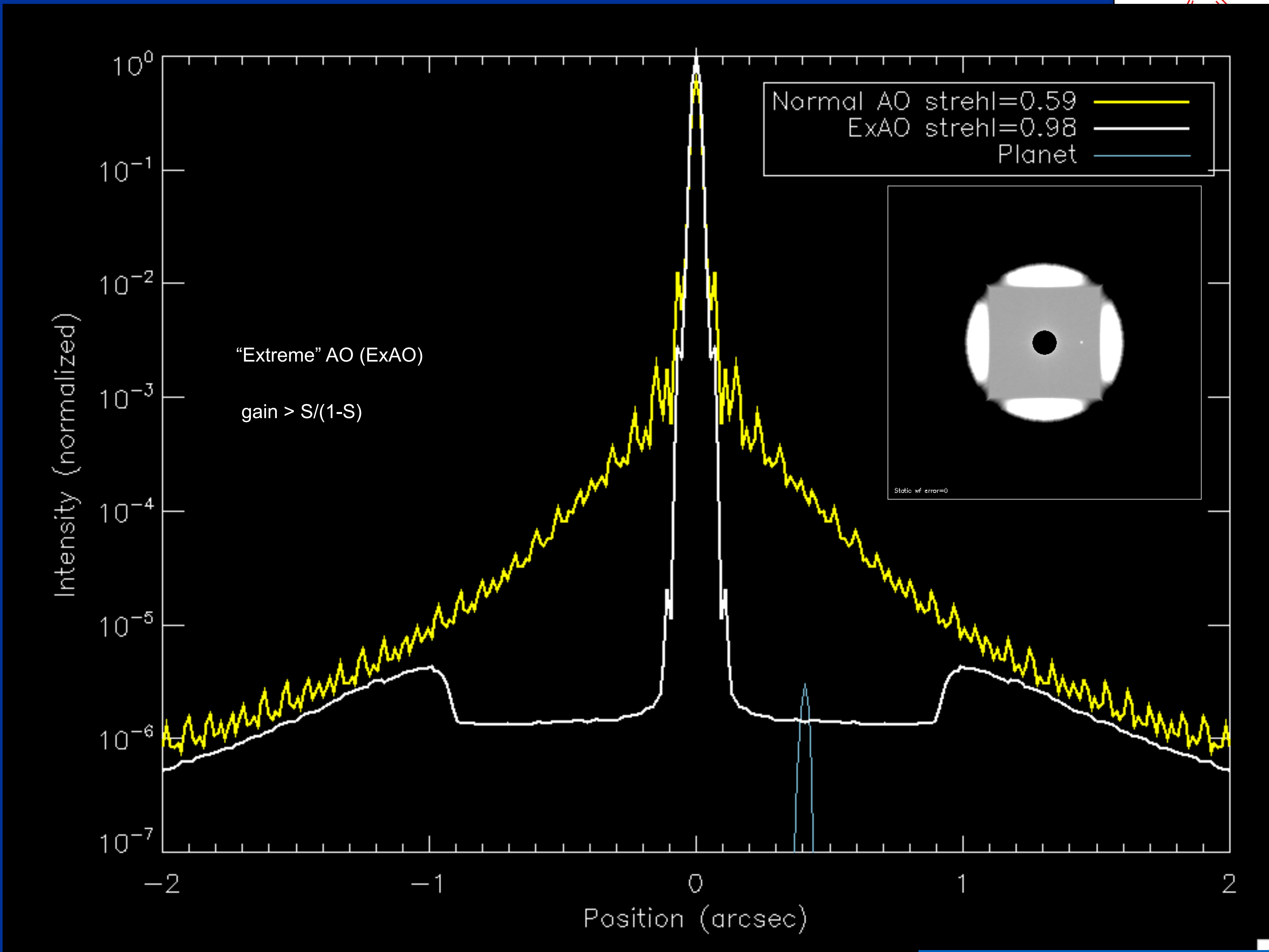
SCExAO

Guyon et al, 10

Credit: Claire E. Max, UCSC

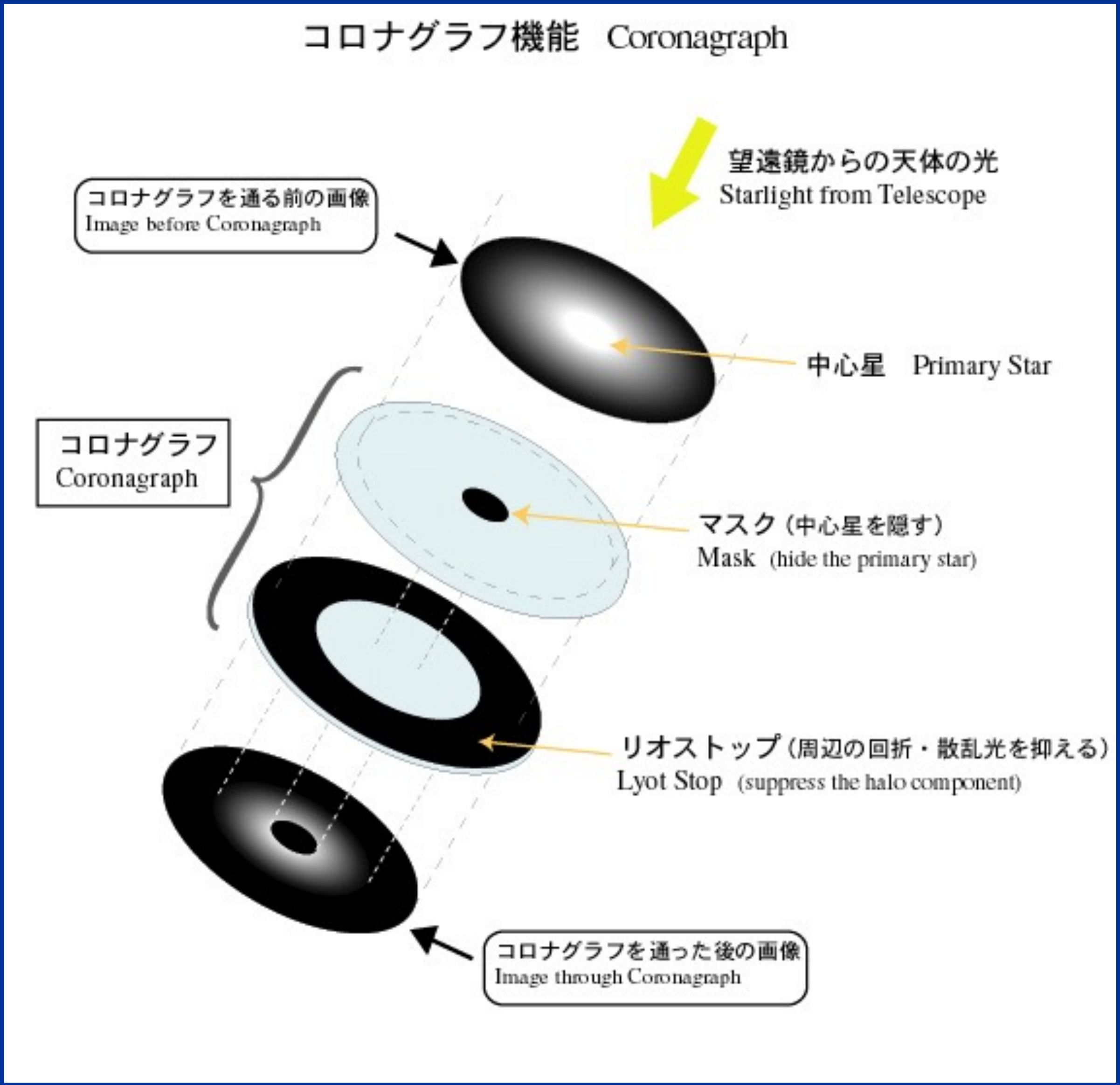



**Credit: Claire E. Max, UCSC**




**Credit: Claire E. Max, UCSC**

# Cartoon of Lyot Coronagraph

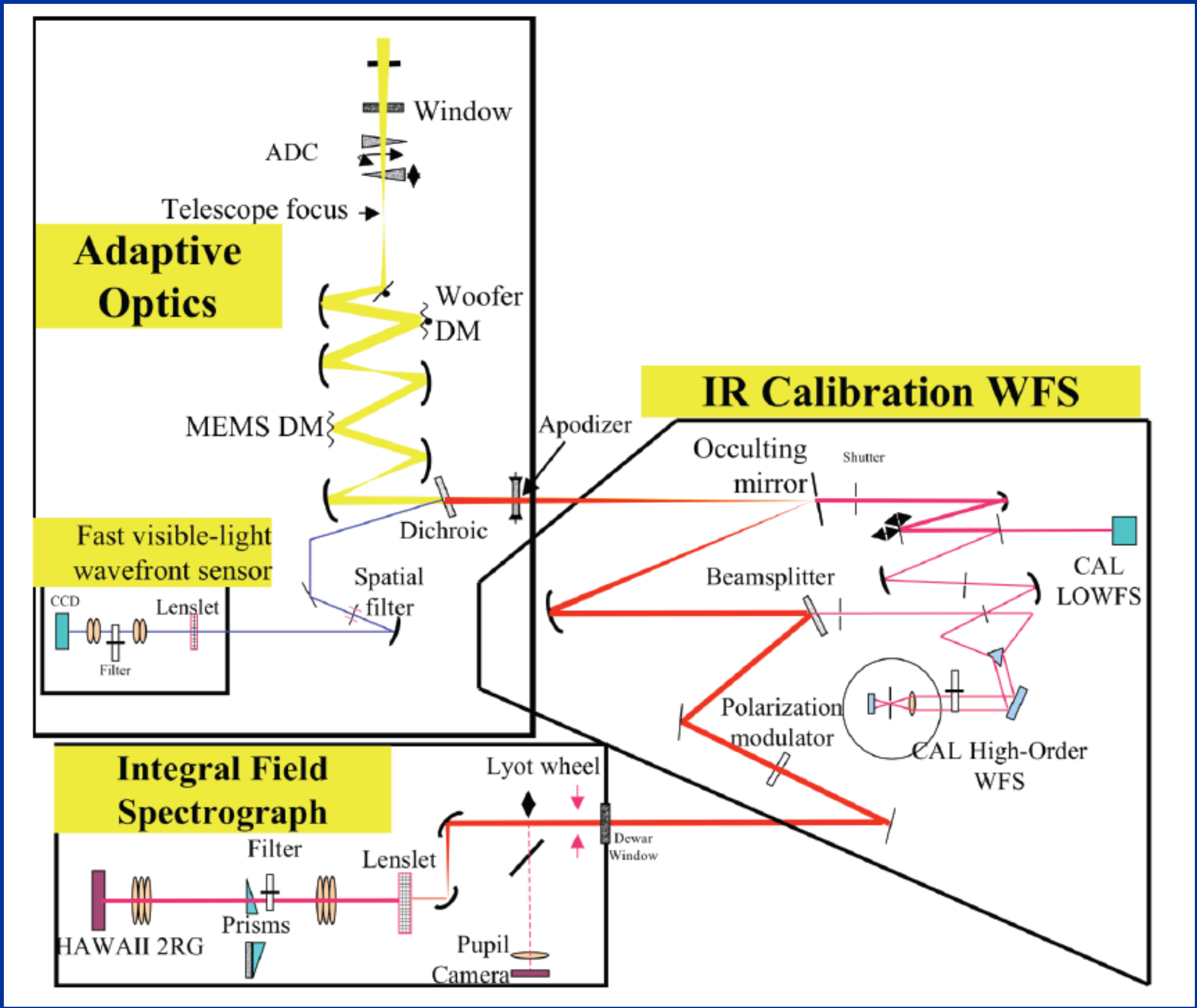



Credit: Subaru website



Credit: Claire E. Max, UCSC

# Schematic of Gemini Planet Imager






Credit: Claire E. Max, UCSC

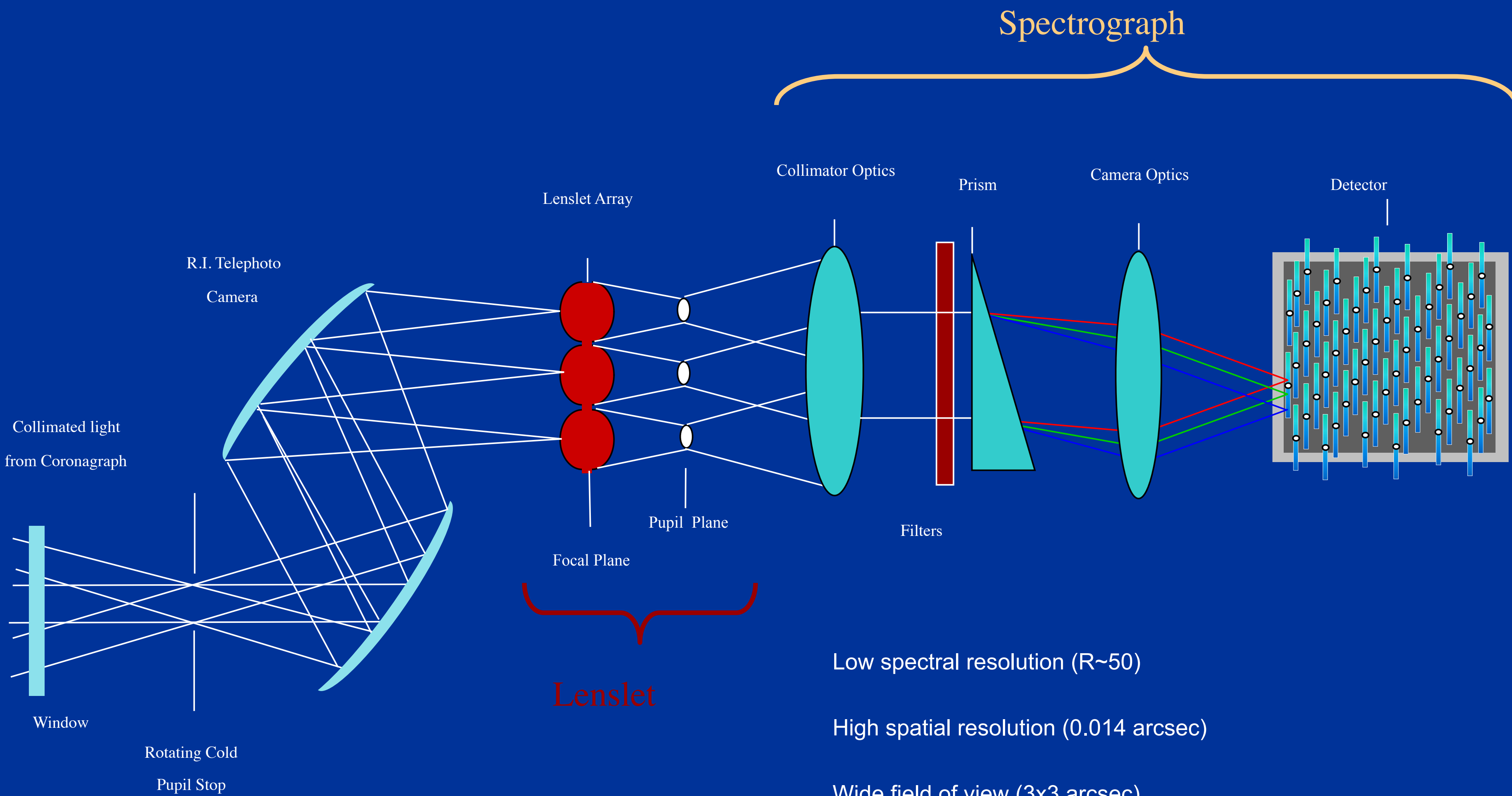
# Comparison of original Keck AO and GPI AO parameters

| | Keck AO (1999) | GPI (2010) |
|---|---|---|
| Deformable mirror | 349 actuators<br>(240 active) | 4096 actuators<br>(1809 active) |
| Subaperture | 56 cm | 18 cm |
| Control rate | 670 Hz | 2000 Hz |
| Wavefront sensor | Shack-Hartmann<br>400 – 1000 nm | Spatially-filtered Shack-Hartmann<br>700-900 nm |
| Strehl @ 1.65 μm | 40% | > 90% |
| Guide star mag (NGS only) | $R < 13.5$ mag. | $I < 9$ mag.<br>( V < 11) |



Credit: Claire E. Max, UCSC

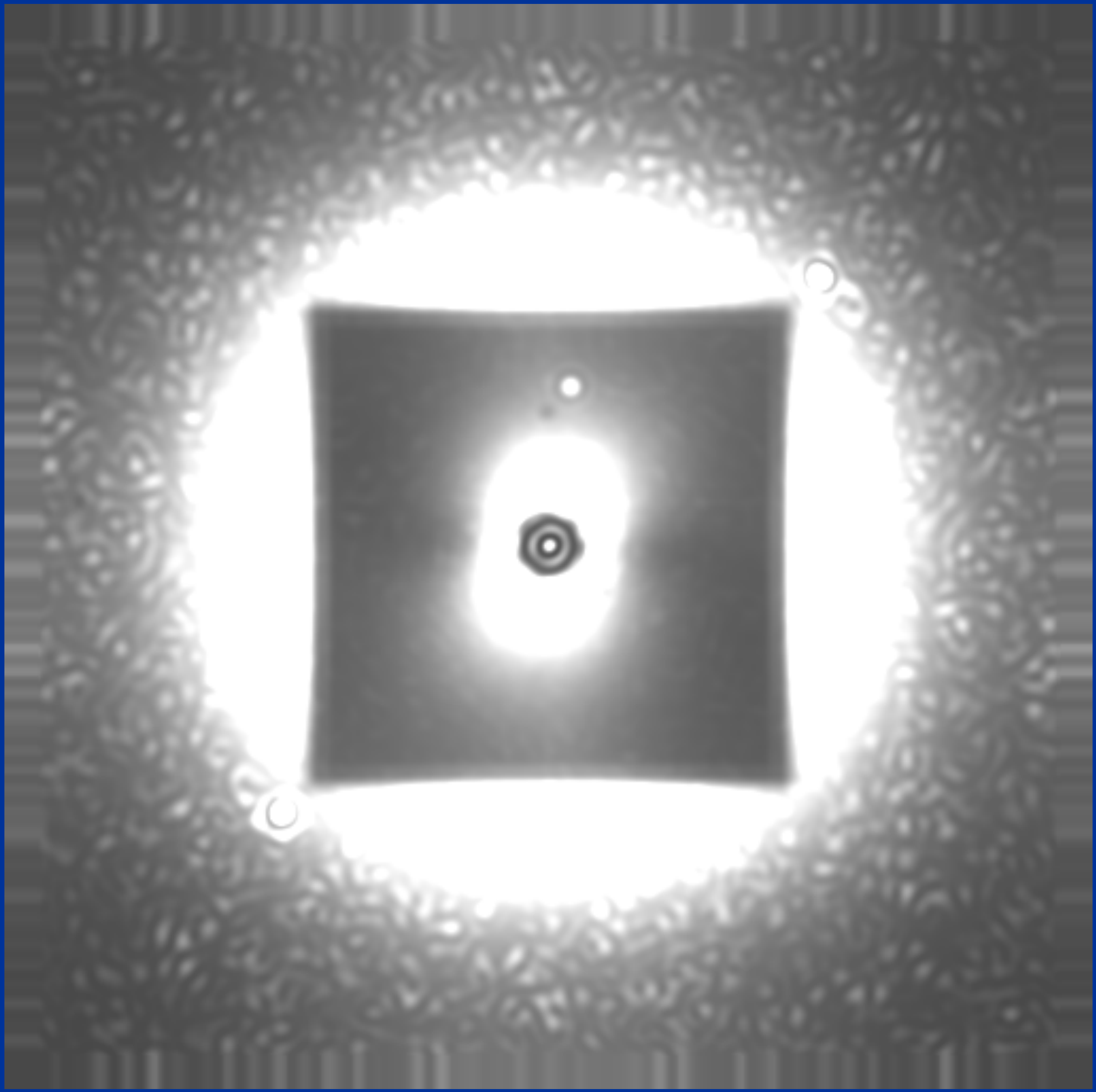
# GPI Integral field spectrograph (James Larkin, UCLA)




- Low spectral resolution (R~50)
- High spatial resolution (0.014 arcsec)
- Wide field of view (3x3 arcsec)
- Minimal scattered light

**Credit: Claire E. Max, UCSC**

# *Data pipeline assembles cubes: image of planet as function of wavelength*

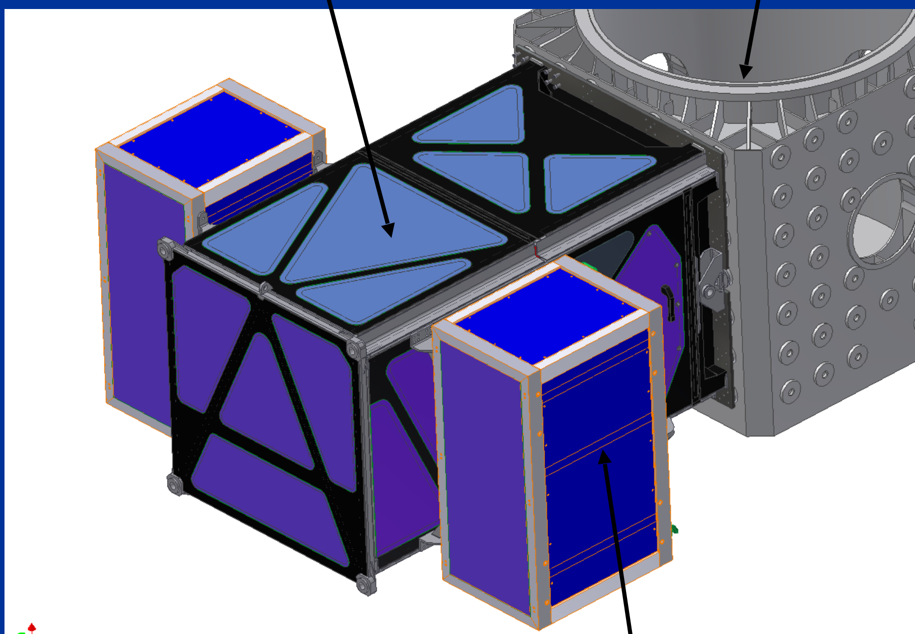


Christian Marois, HIA

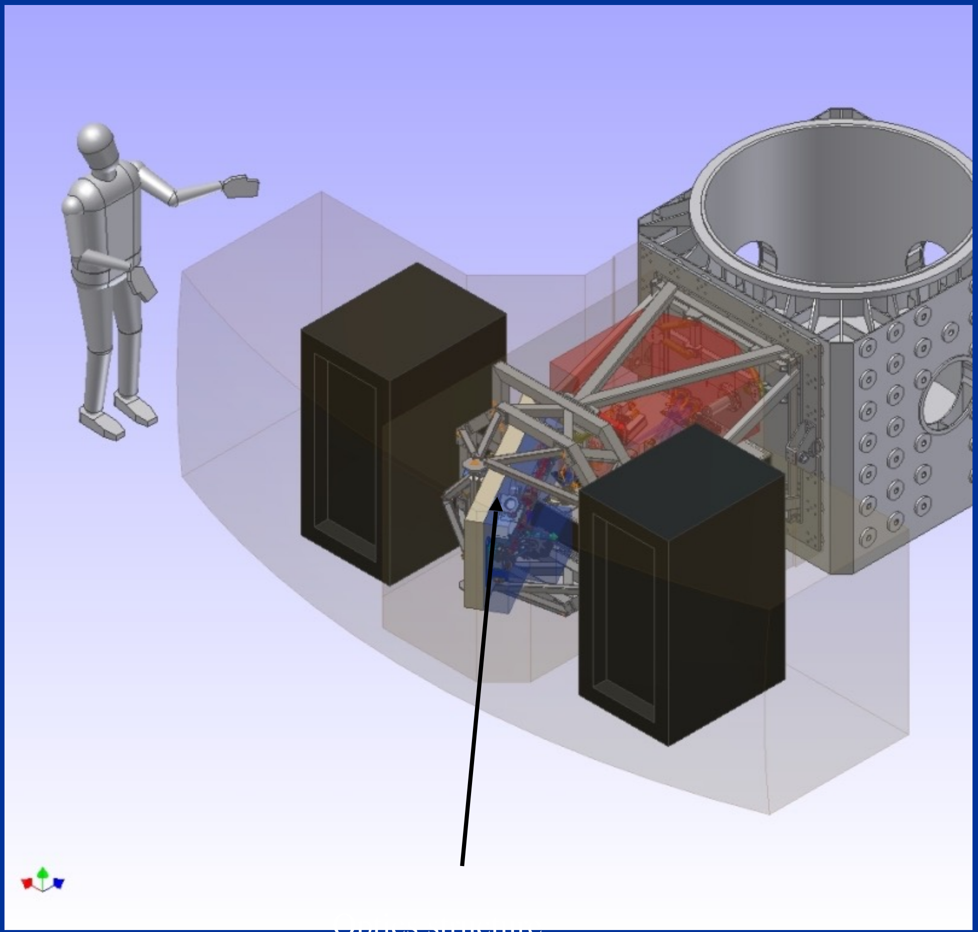
# GPI mechanical design

Gemini Cassegrain support structure

GPI enclosure



Electronics

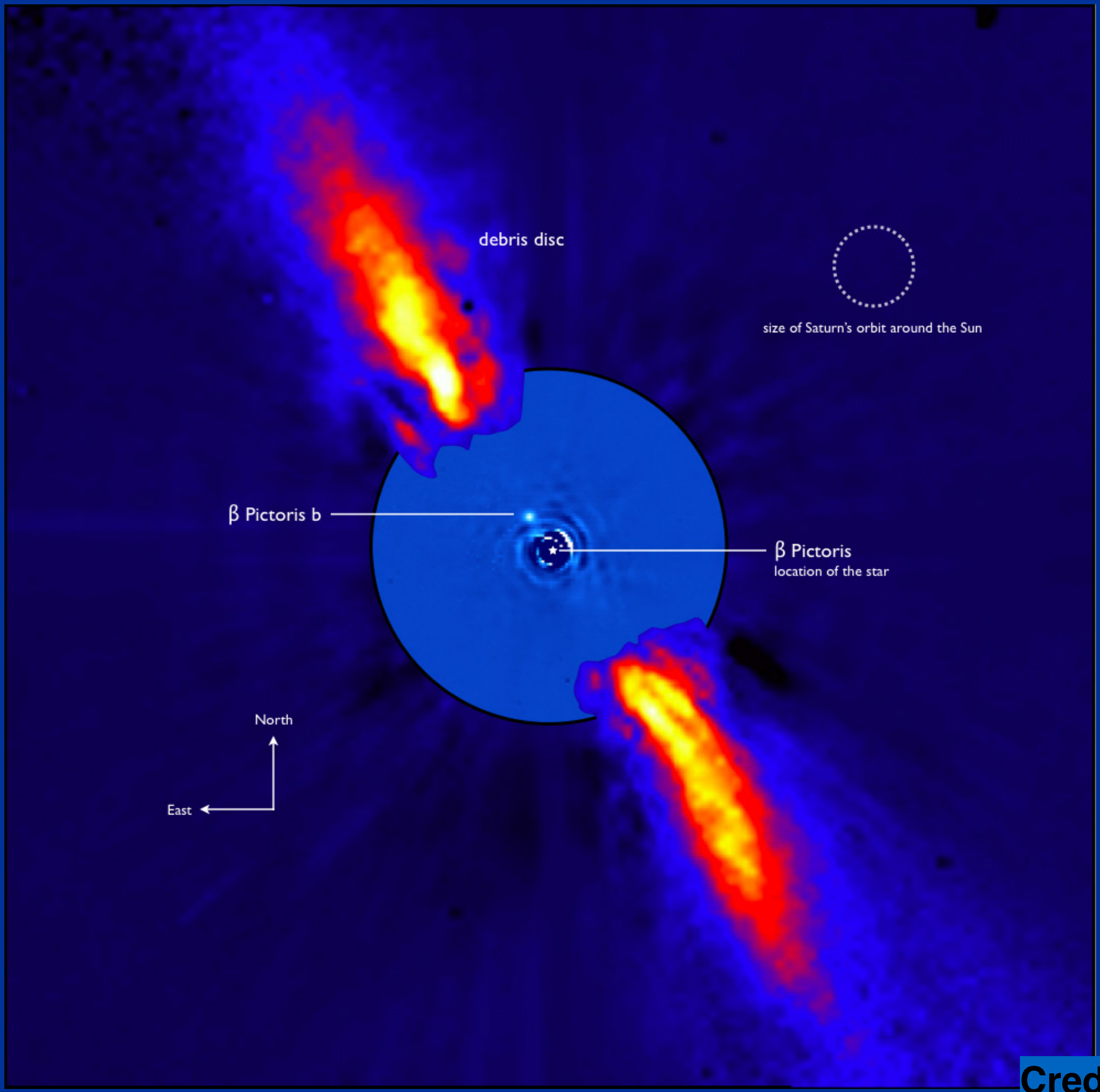


Optics structure



Credit: Claire E. Max, UCSC

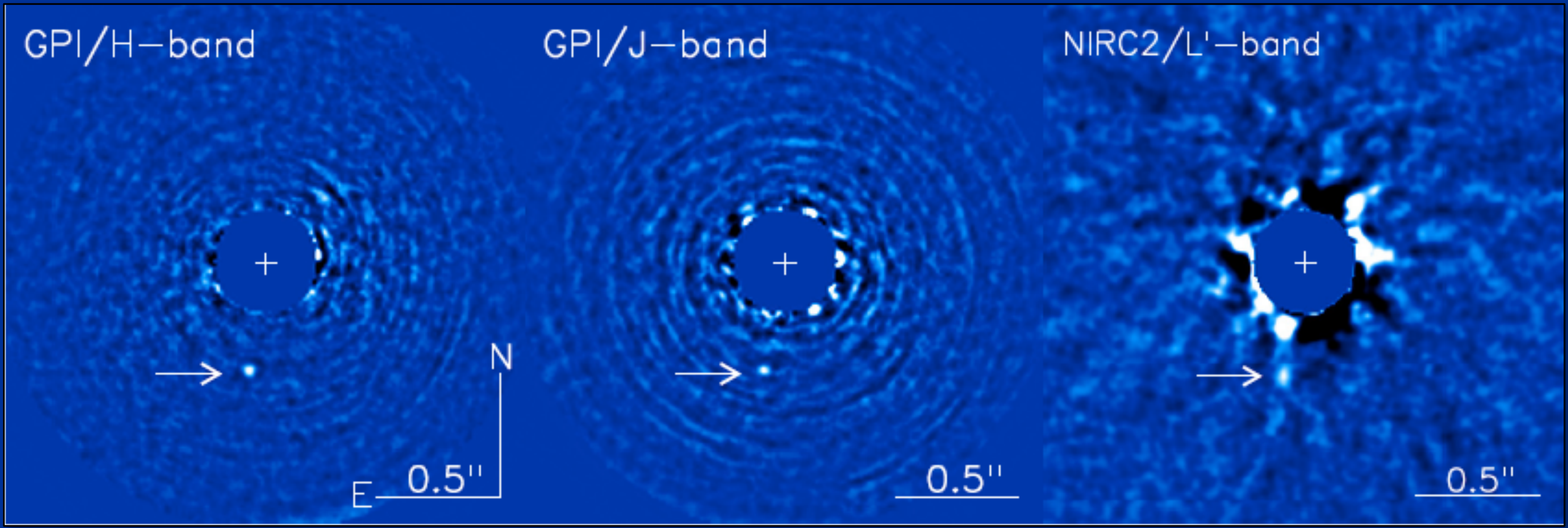
# Beta Pictoris b: a planet within a disk

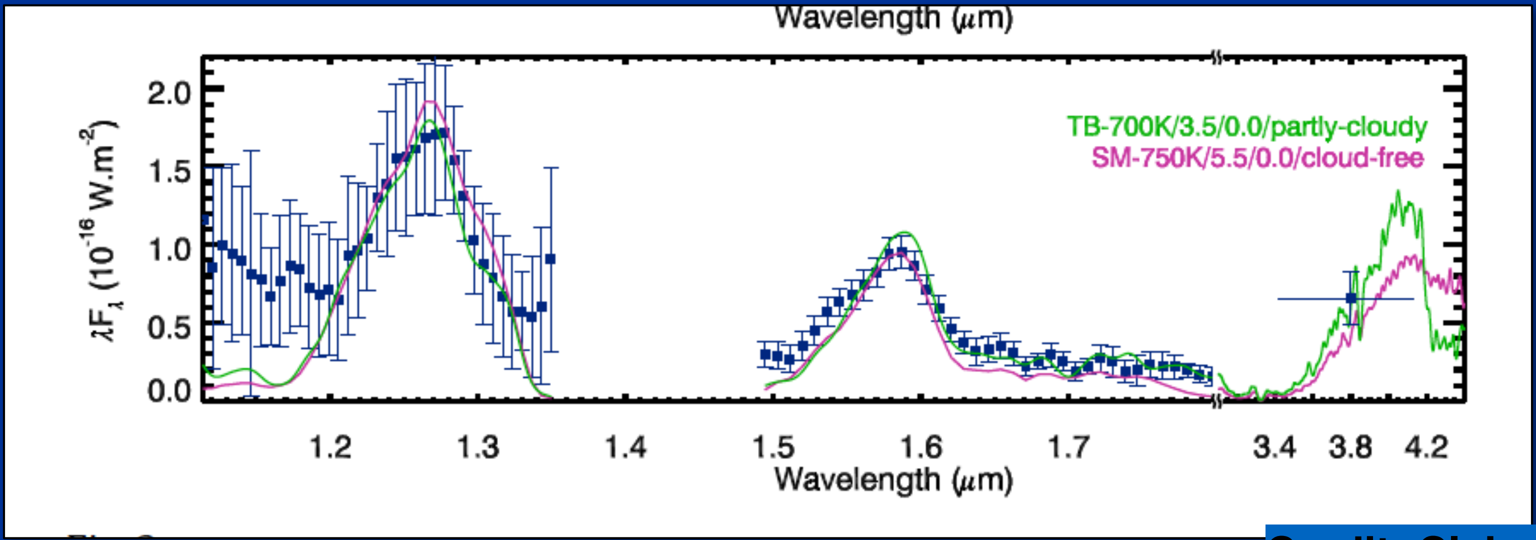





Credit: Claire E. Max, UCSC

# 51 Eri b: from GPI (Macintosh et al. 2015)

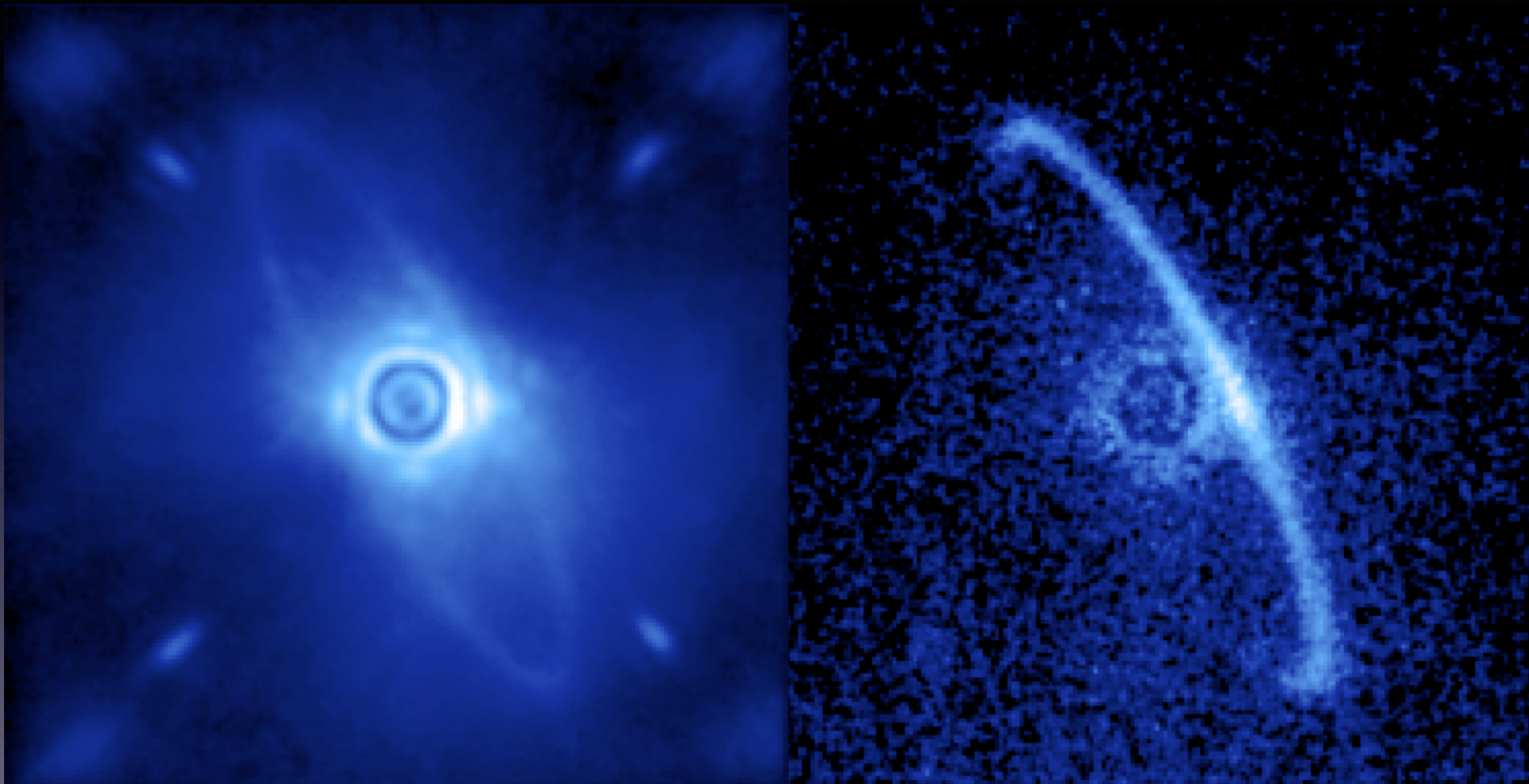


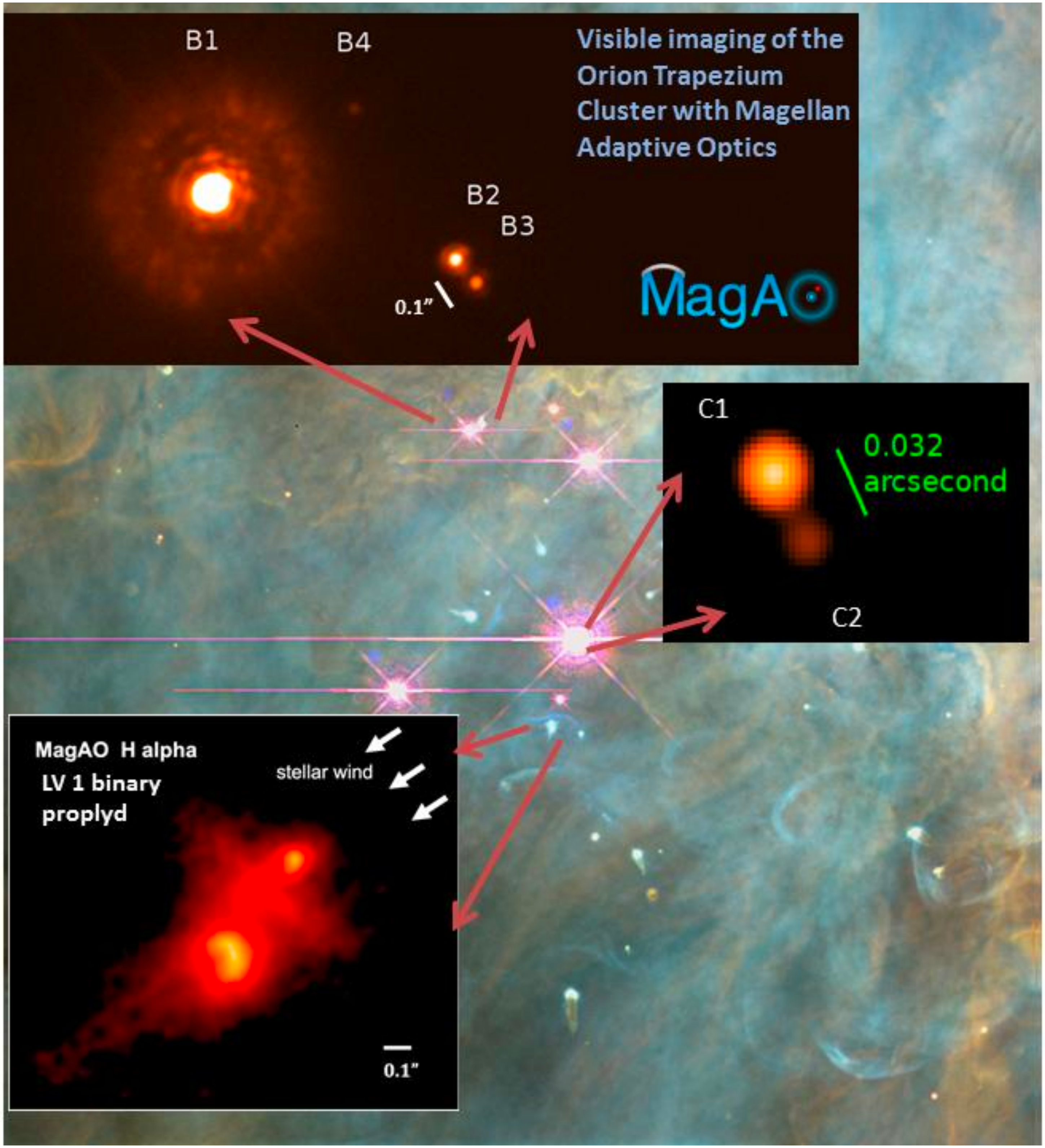



Credit: Claire E. Max, UCSC

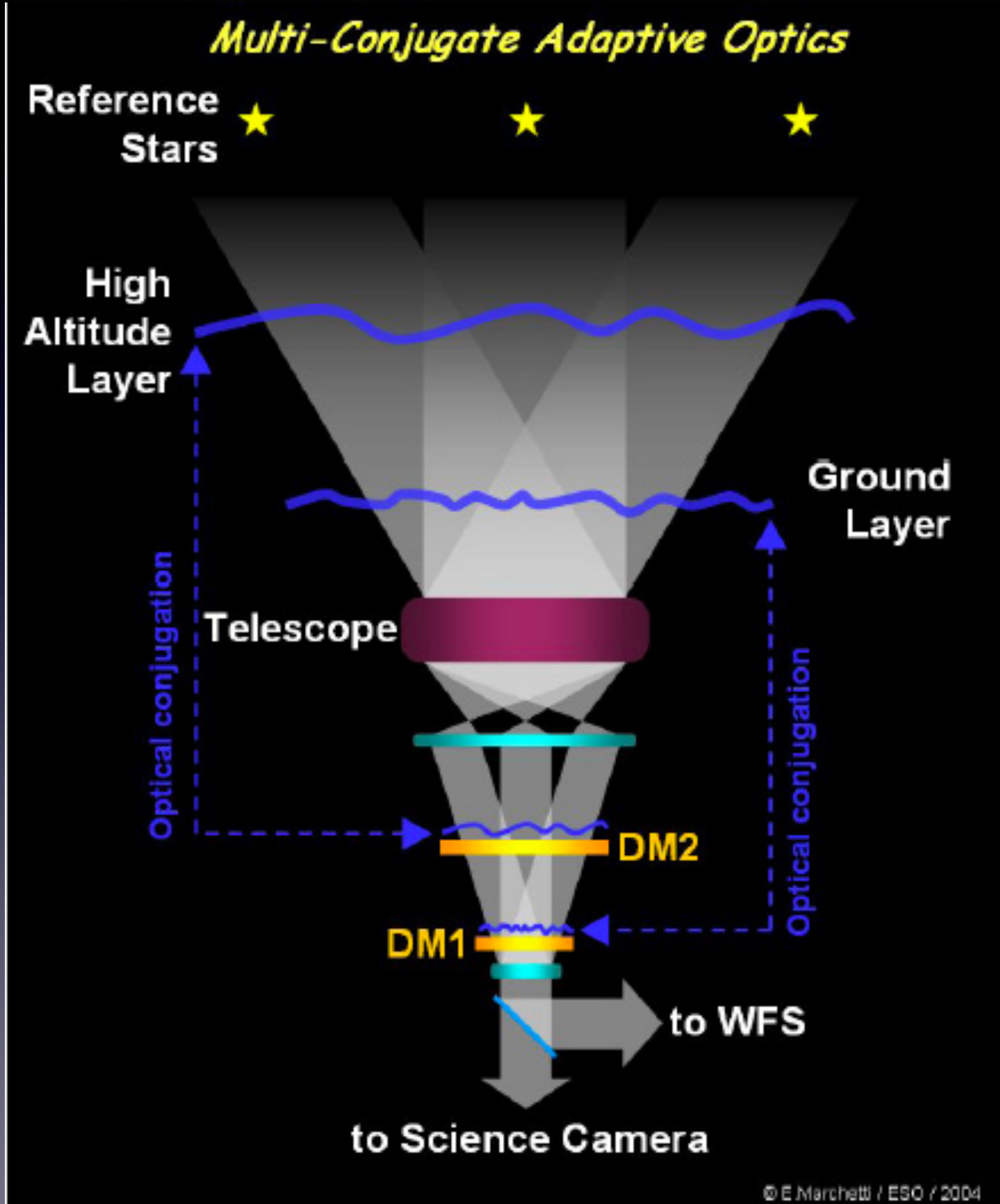
# Current AO Capabilities - GPI



HR4796A

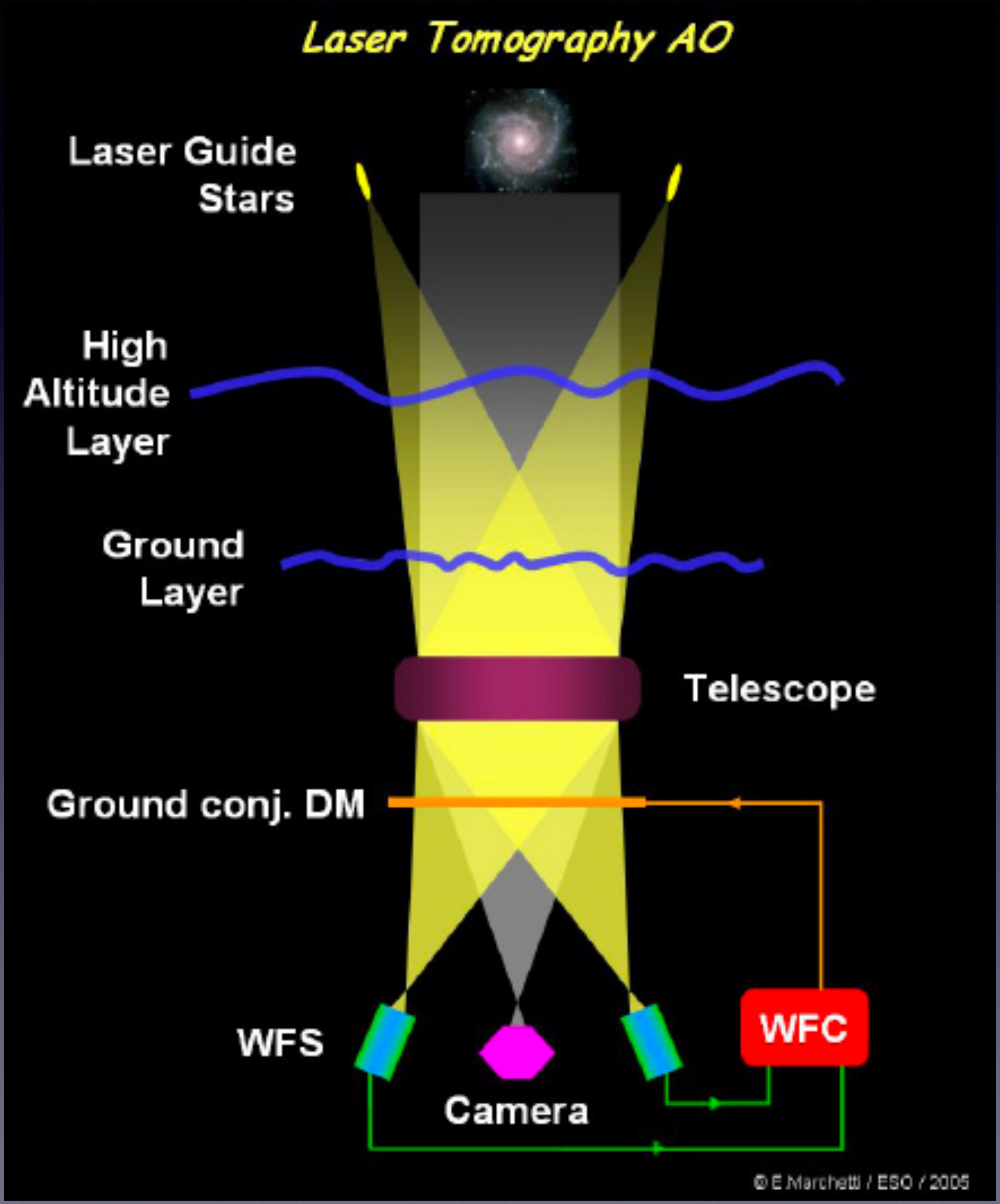


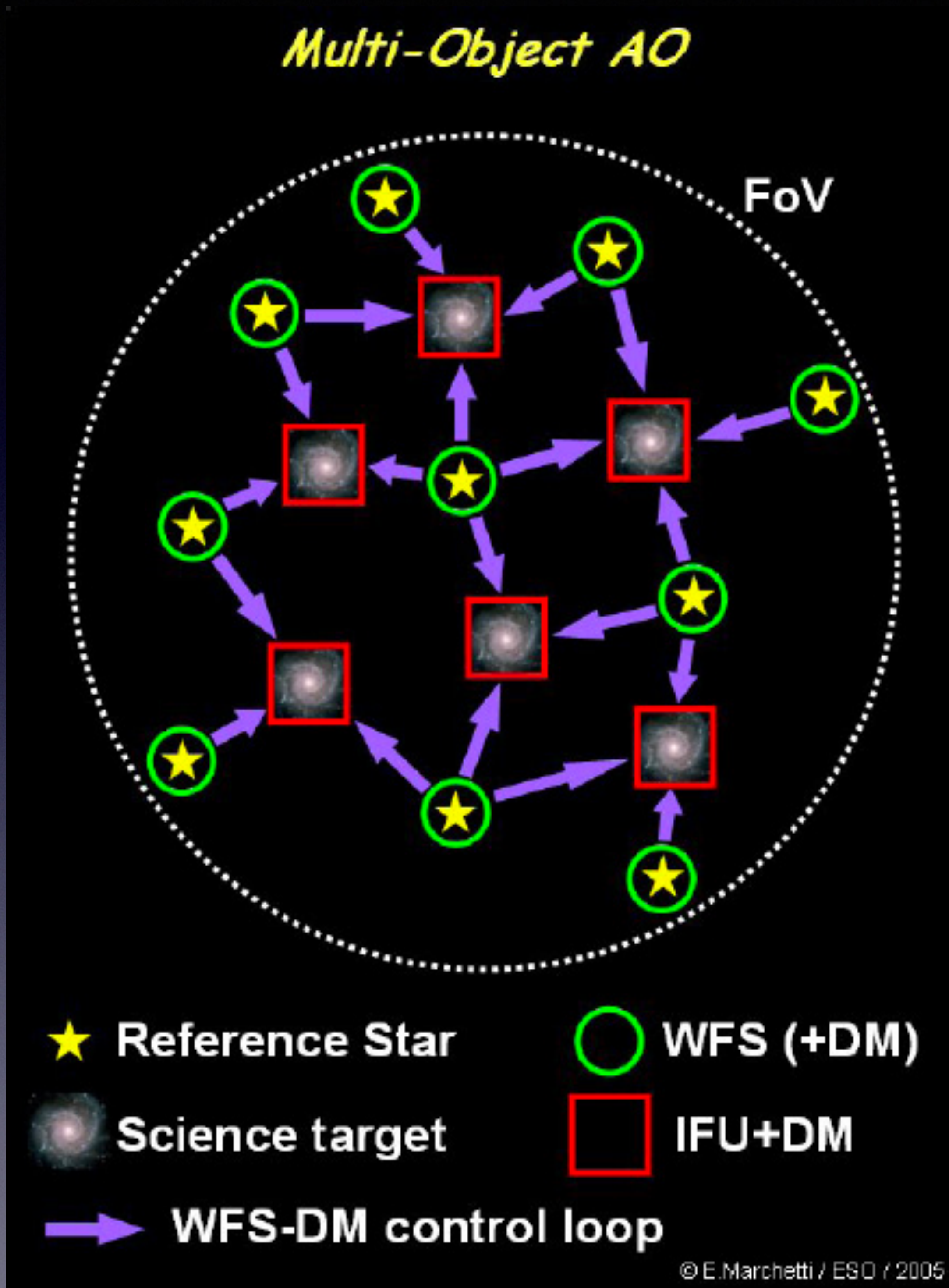
Visible imaging of the Orion Trapezium Cluster with Magellan Adaptive Optics
B1
B4
B2
B3
0.1"
MagAO
C1
0.032 arcsecond
C2
MagAO H alpha
LV 1 binary proplyd
stellar wind
0.1"



Multi-Conjugate Adaptive Optics
Reference Stars
High Altitude Layer
Ground Layer
Telescope
Optical conjugation
Optical conjugation
DM2
DM1
to WFS
to Science Camera
© E.Marchetti / ESO / 2004


GeMS Laser Constellation
Jan 22, 2011

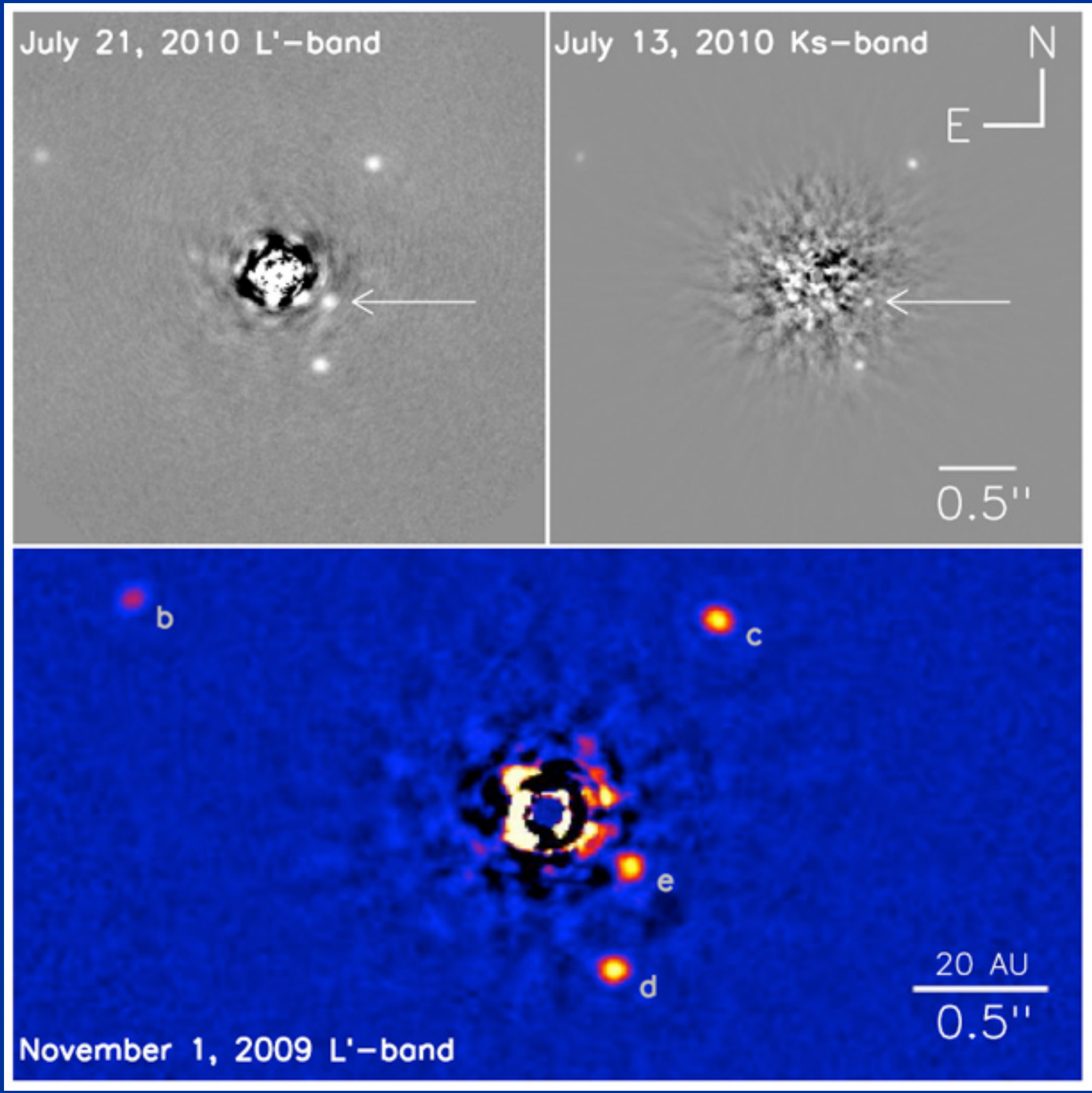

Laser Tomography AO
Laser Guide Stars
High Altitude Layer
Ground Layer
Telescope
Ground conj. DM
WFS
Camera
WFC
© E.Marchetti / ESO / 2005


Multi-Object AO
FoV
Reference Star
WFS (+DM)
Science target
IFU+DM
WFS-DM control loop
© E.Marchetti / ESO / 2005

# Adaptive Optics:

- Corrects for the image degradation due to the atmosphere.
- This is done by combining a fast wavefront sensor(s) with a fast deformable mirror(s).
- It allows large telescopes ($> r_0 \sim 10$ cm) to achieve the diffraction limit.
- For seeing limited telescopes, signal-to-noise goes as the diameter squared ($D^2$).
- For diffraction limited telescopes (i.e. AO), signal-to-noise goes as $D^4$!
- There are many different types of AO available depending on your science case.

# Directly imaged planets: HR 8799 System

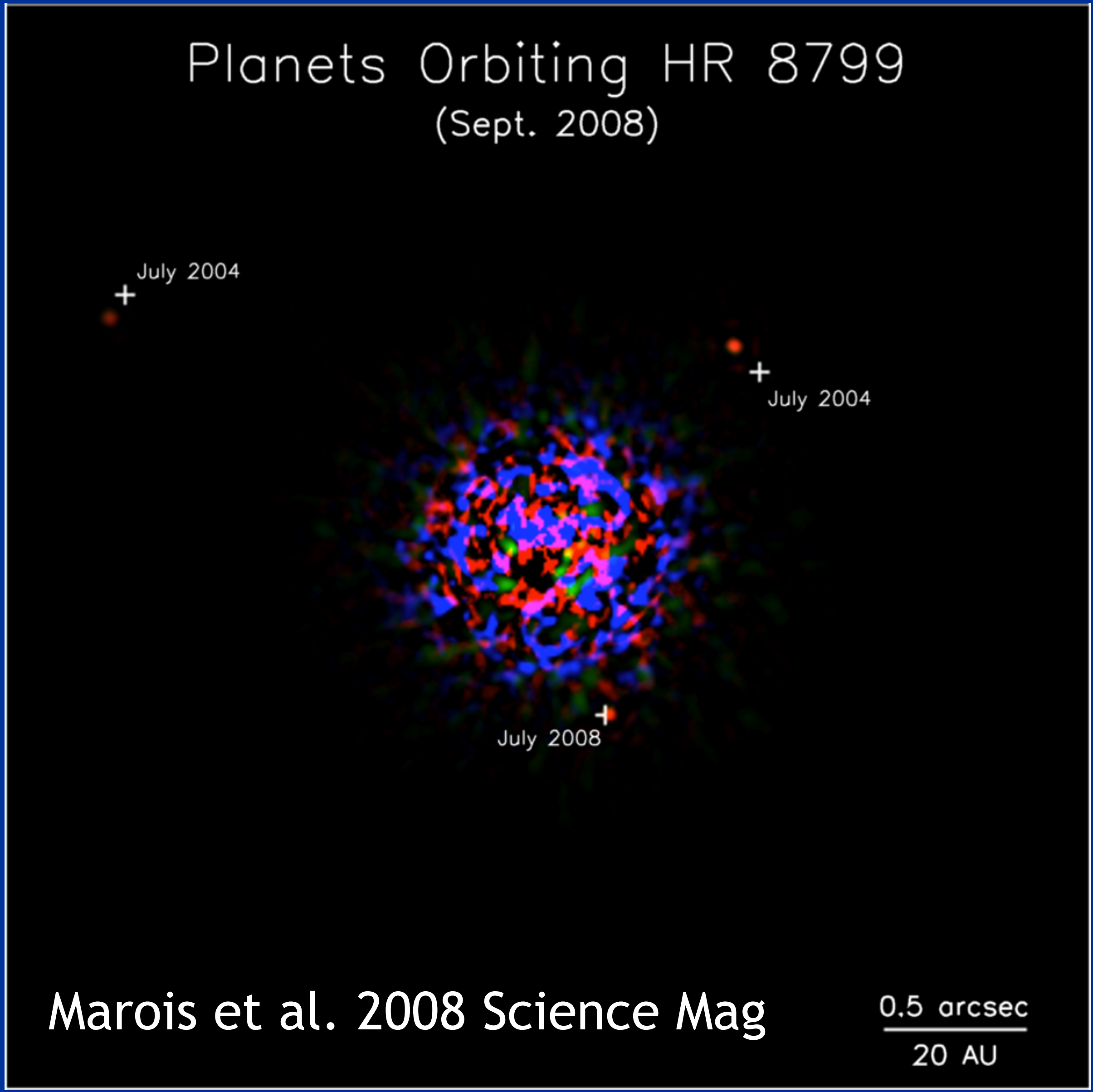



Marois and colleagues, Gemini and Keck



Credit: Claire E. Max, UCSC

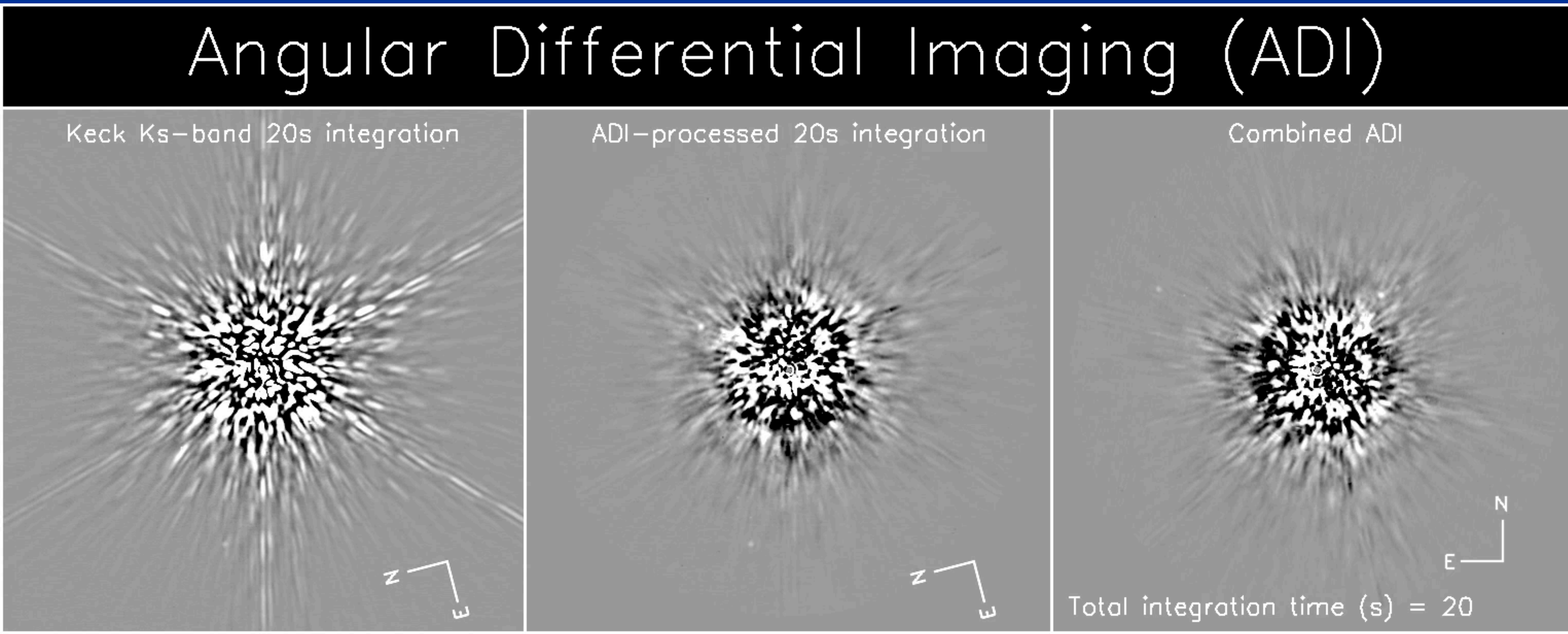
# *First images of an extrasolar planetary system (Keck and Gemini AO)*






Credit: Claire E. Max, UCSC

# Image processing to suppress light from host star

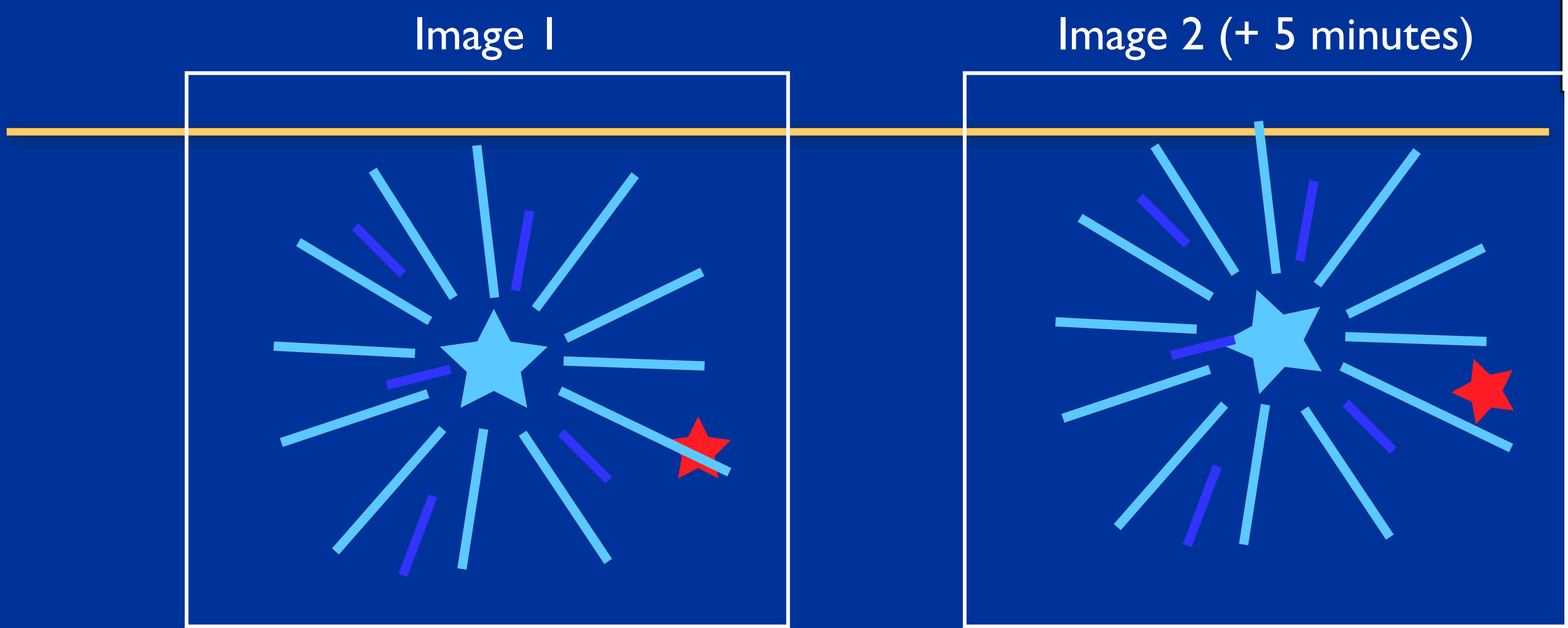


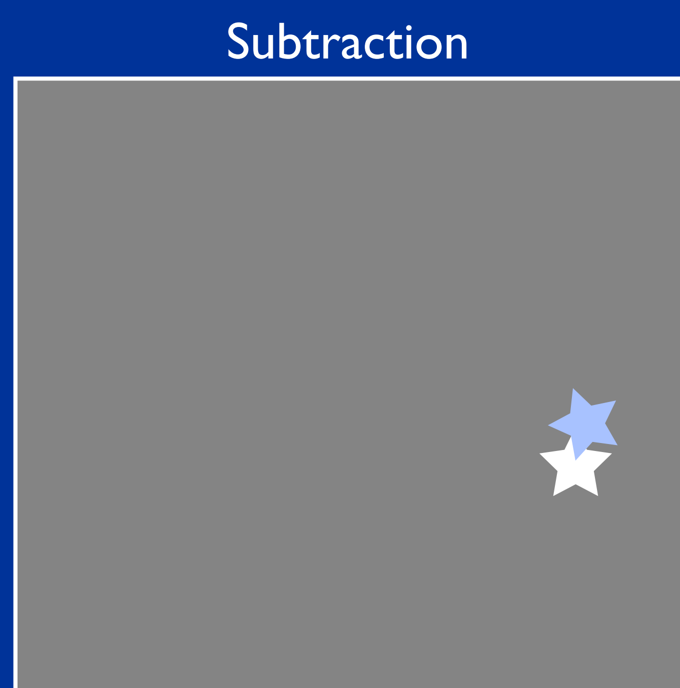

Marois et al.



Credit: Claire E. Max, UCSC

# Angular Differential Imaging

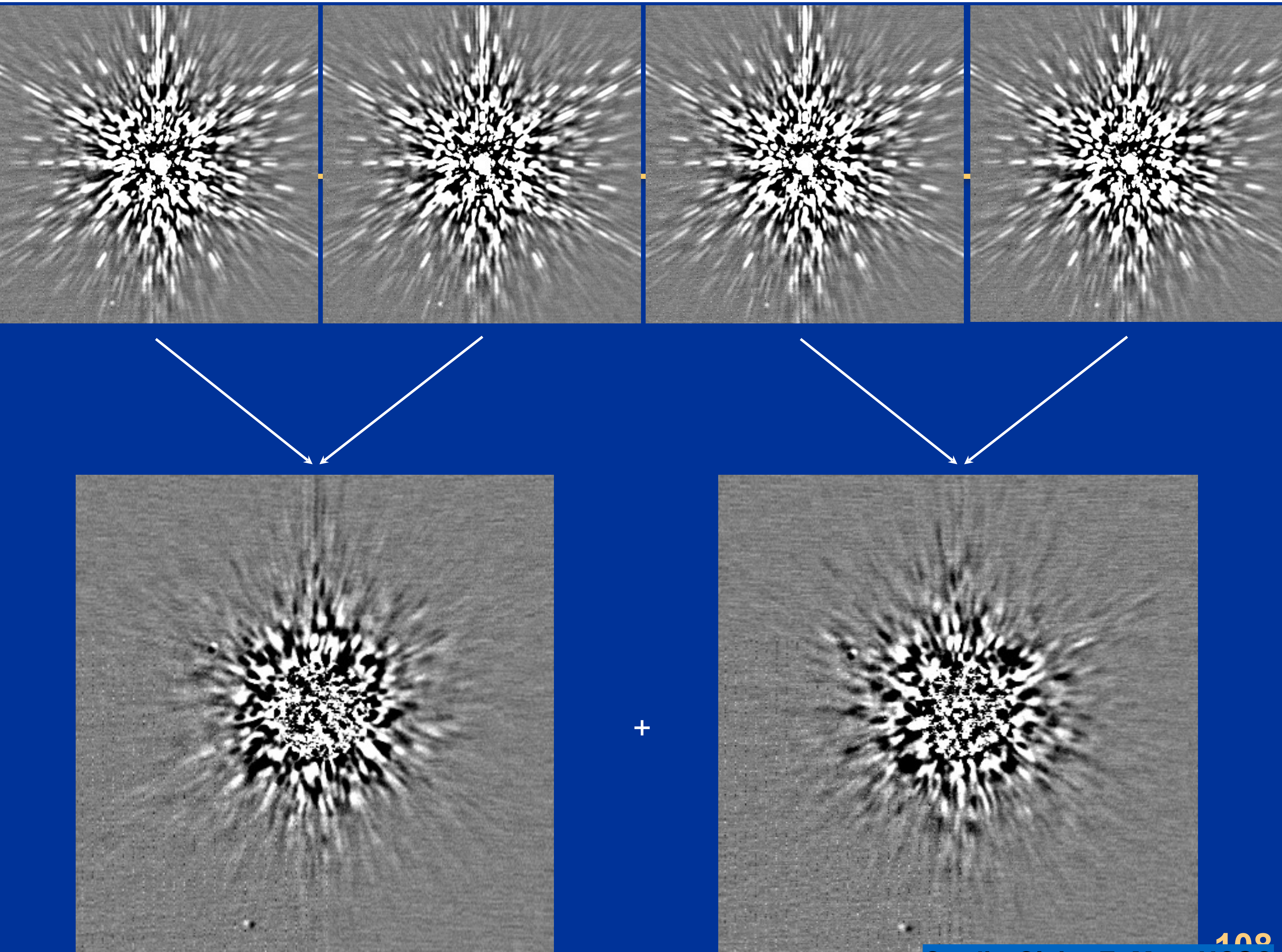


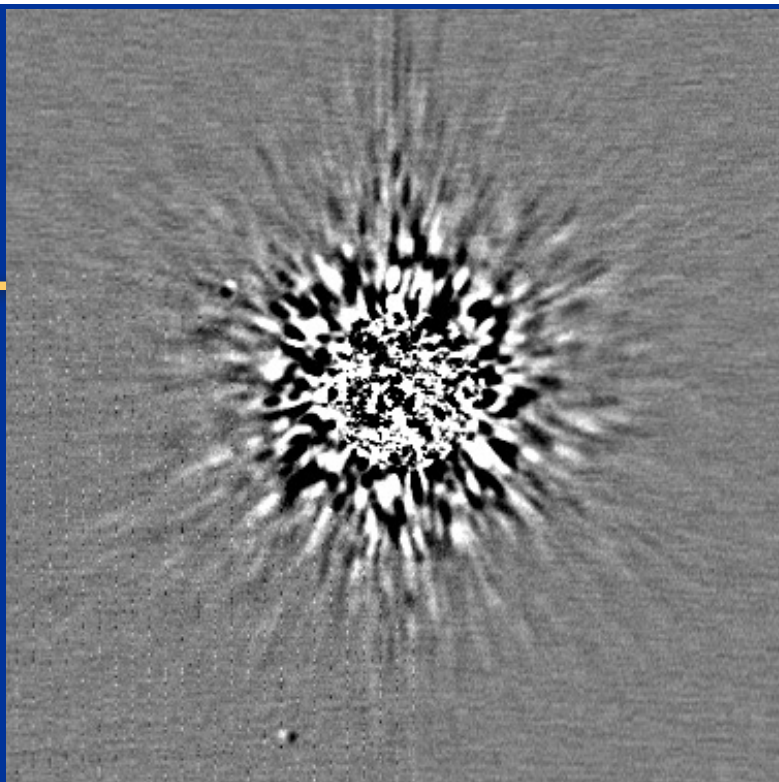

Marois et al 2006



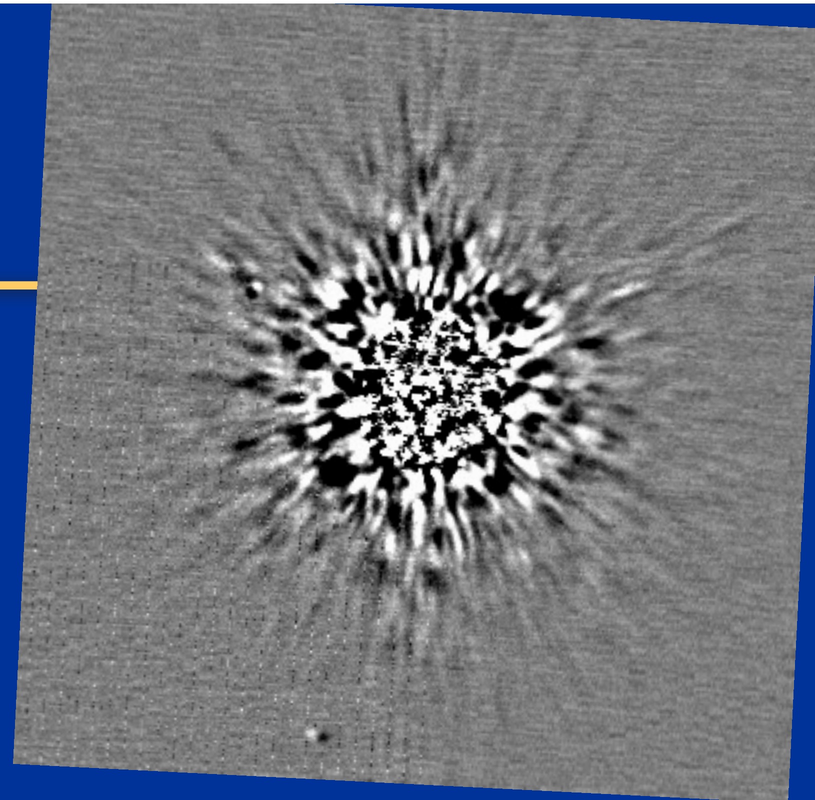
Credit: Claire E. Max, UCSC



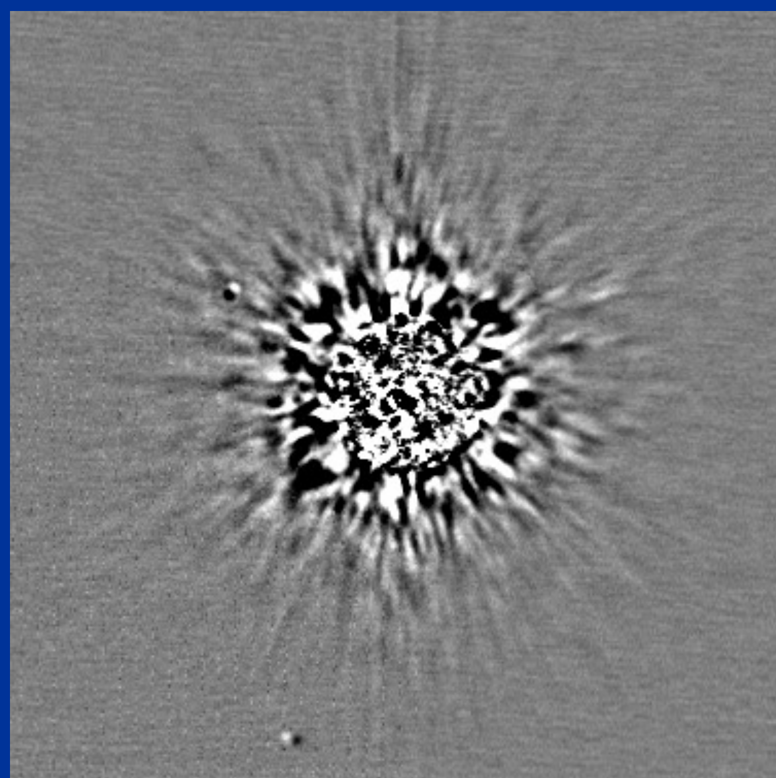

Credit: Claire E. Max, UCSC



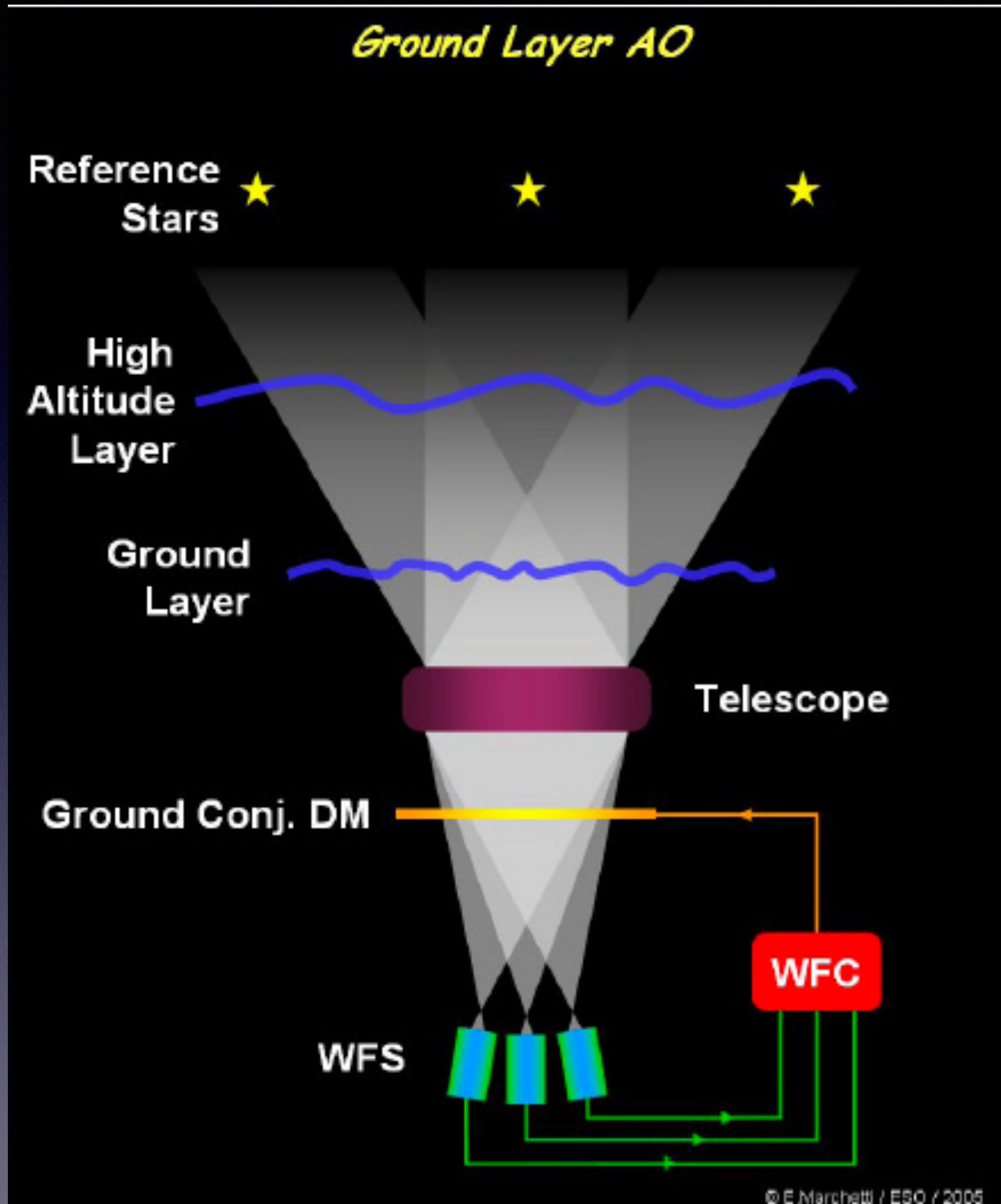
+

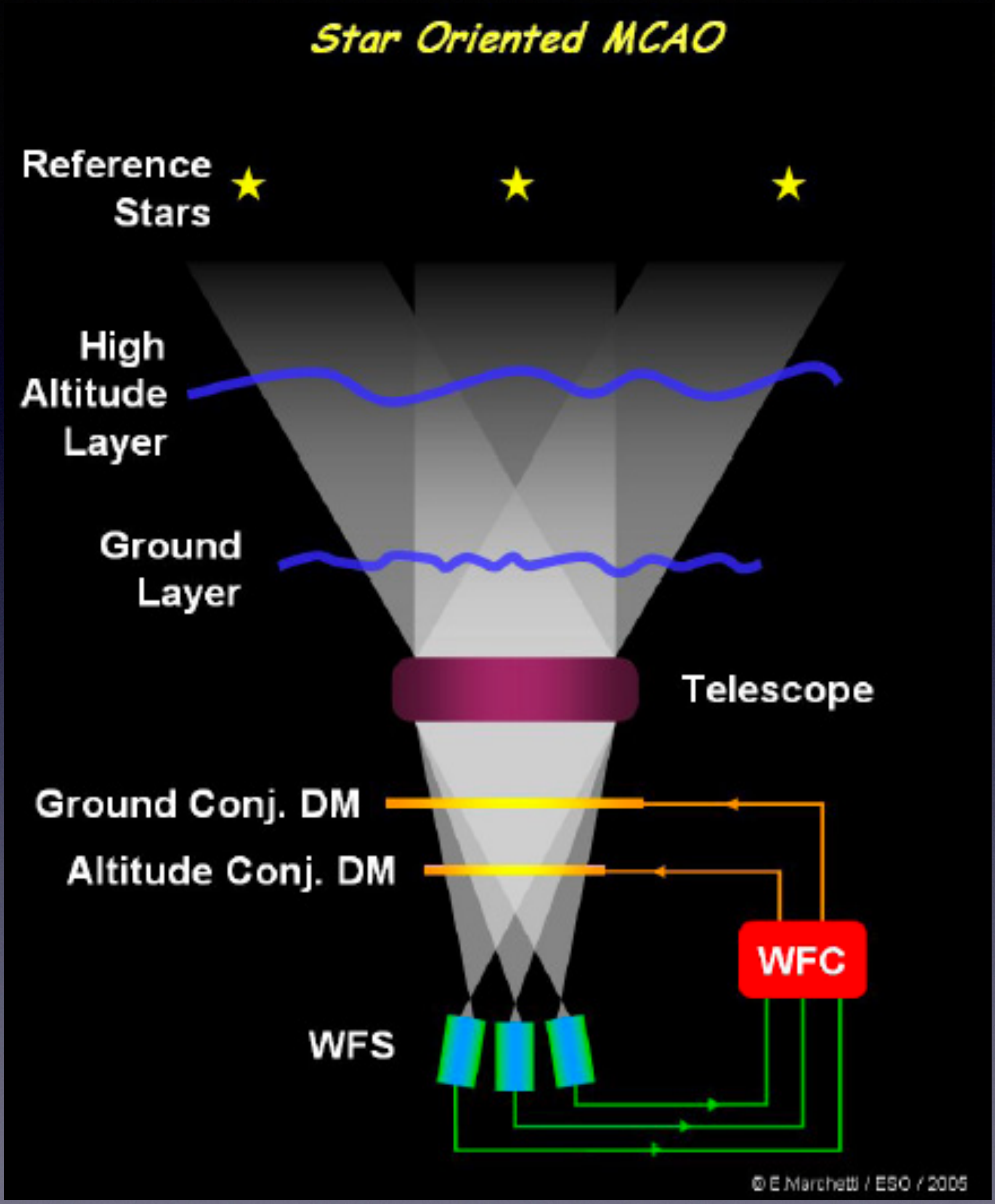


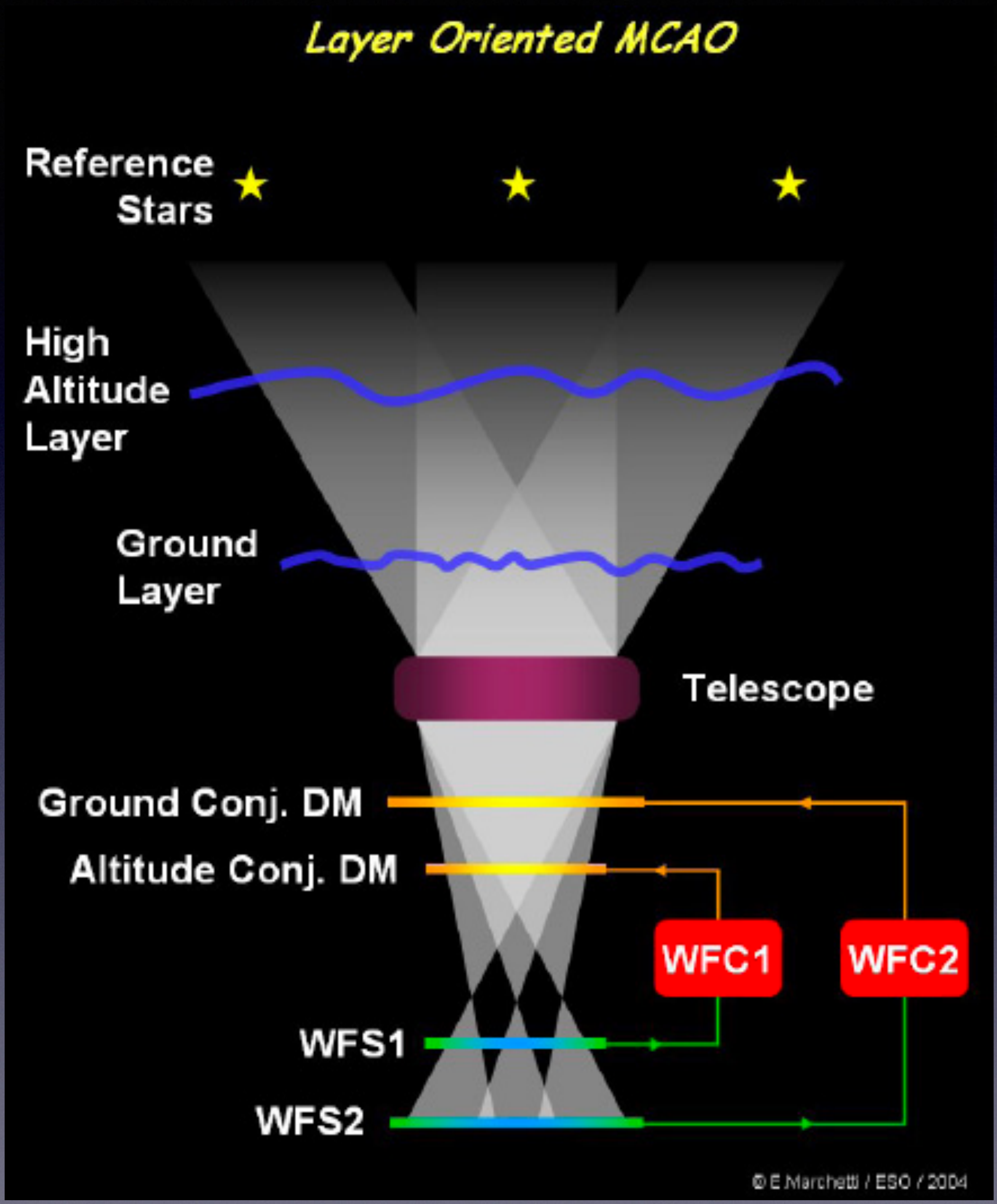
=



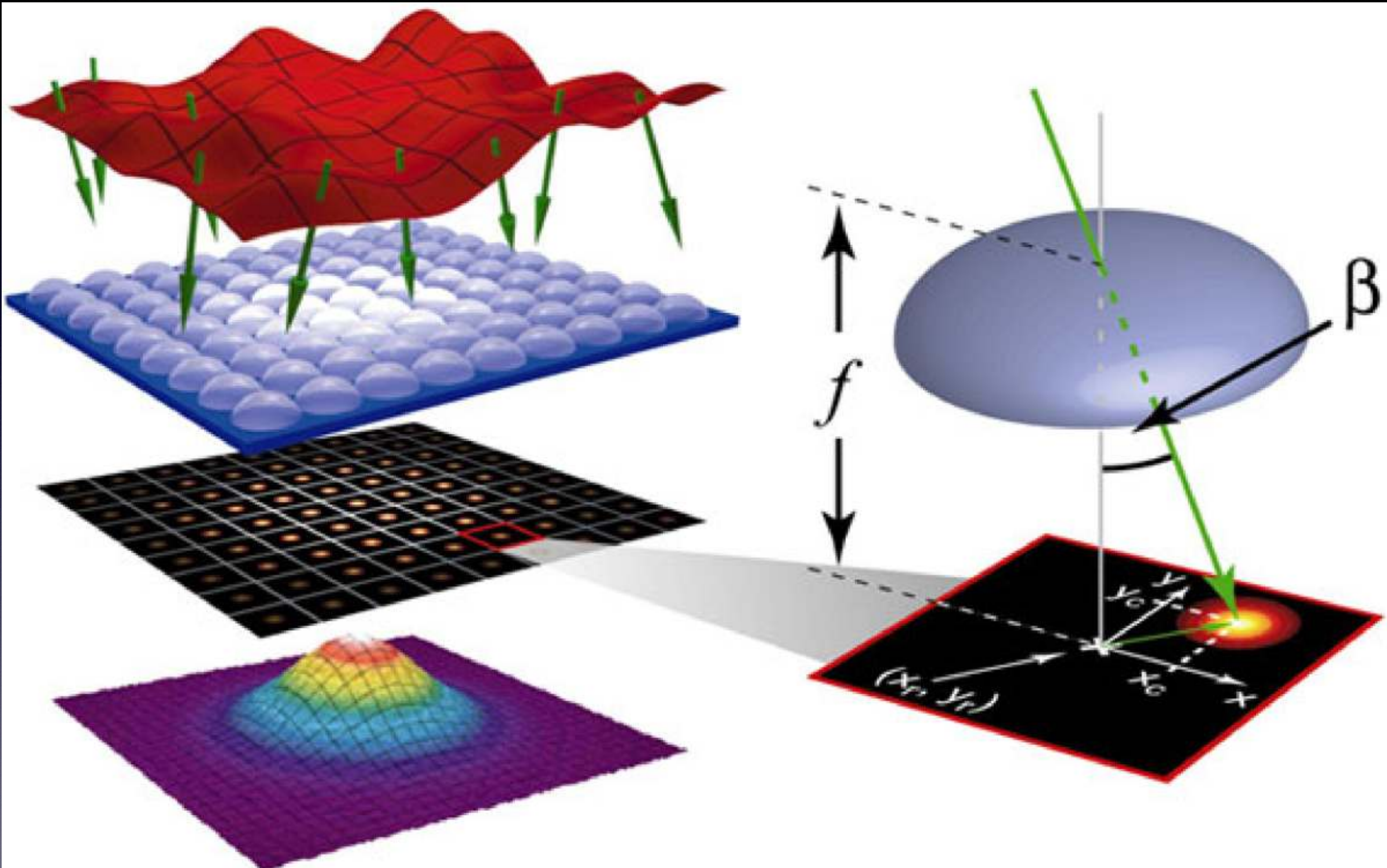
Credit: Claire E. Max, UCSC


Ground Layer AO
Reference Stars
High Altitude Layer
Ground Layer
Telescope
Ground Conj. DM
WFC
WFS
© E.Marchetti / ESO / 2005

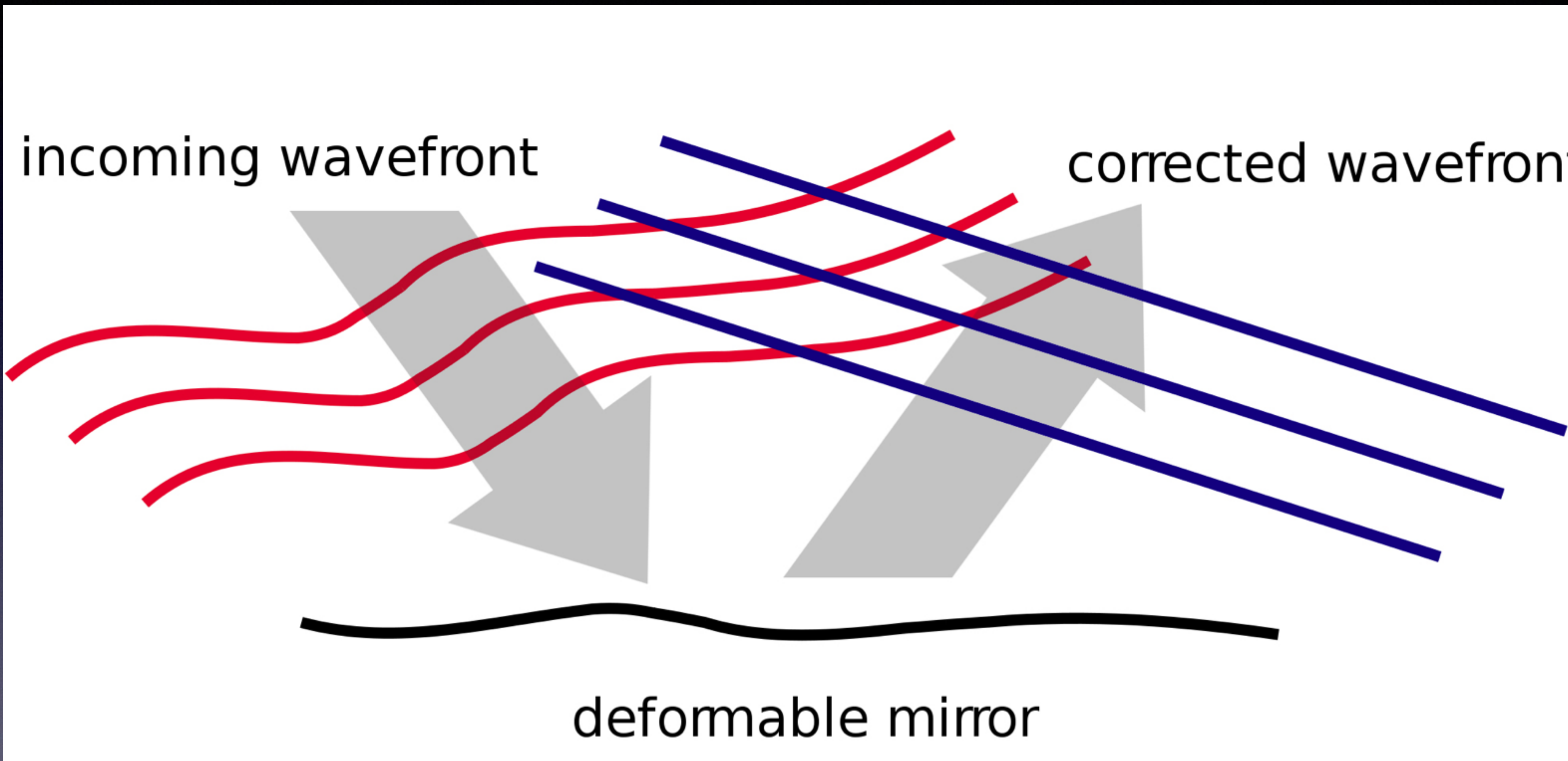

Star Oriented MCAO
Reference Stars
High Altitude Layer
Ground Layer
Telescope
Ground Conj. DM
Altitude Conj. DM
WFC
WFS
© E.Marchetti / ESO / 2005



Layer Oriented MCAO
Reference Stars
High Altitude Layer
Ground Layer
Telescope
Ground Conj. DM
Altitude Conj. DM
WFC1
WFC2
WFS1
WFS2
© E.Marchetti / ESO / 2004



β
f
y
$y_c$
$x_c$
x
$(x_n, y_n)$

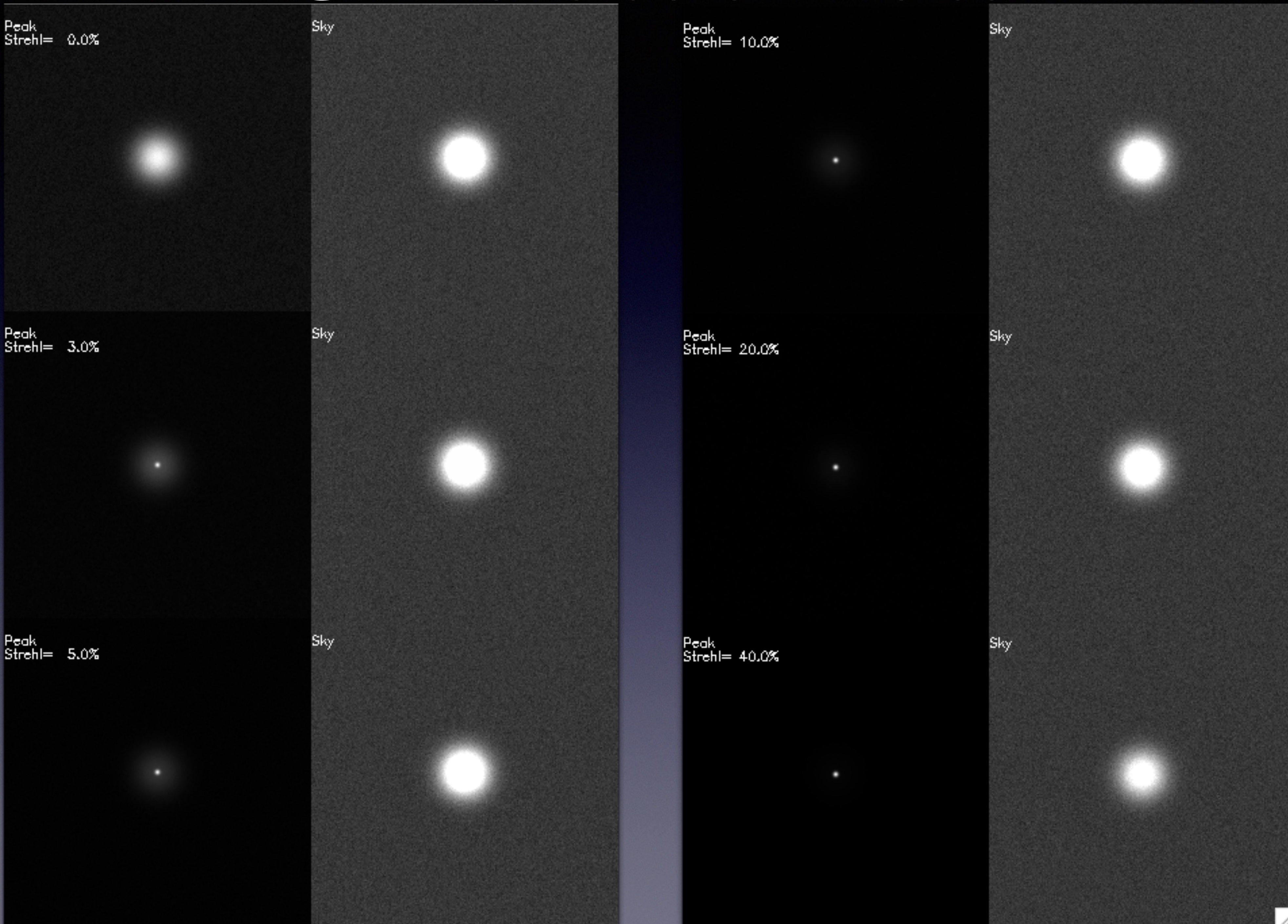

incoming wavefront
corrected wavefront
deformable mirror

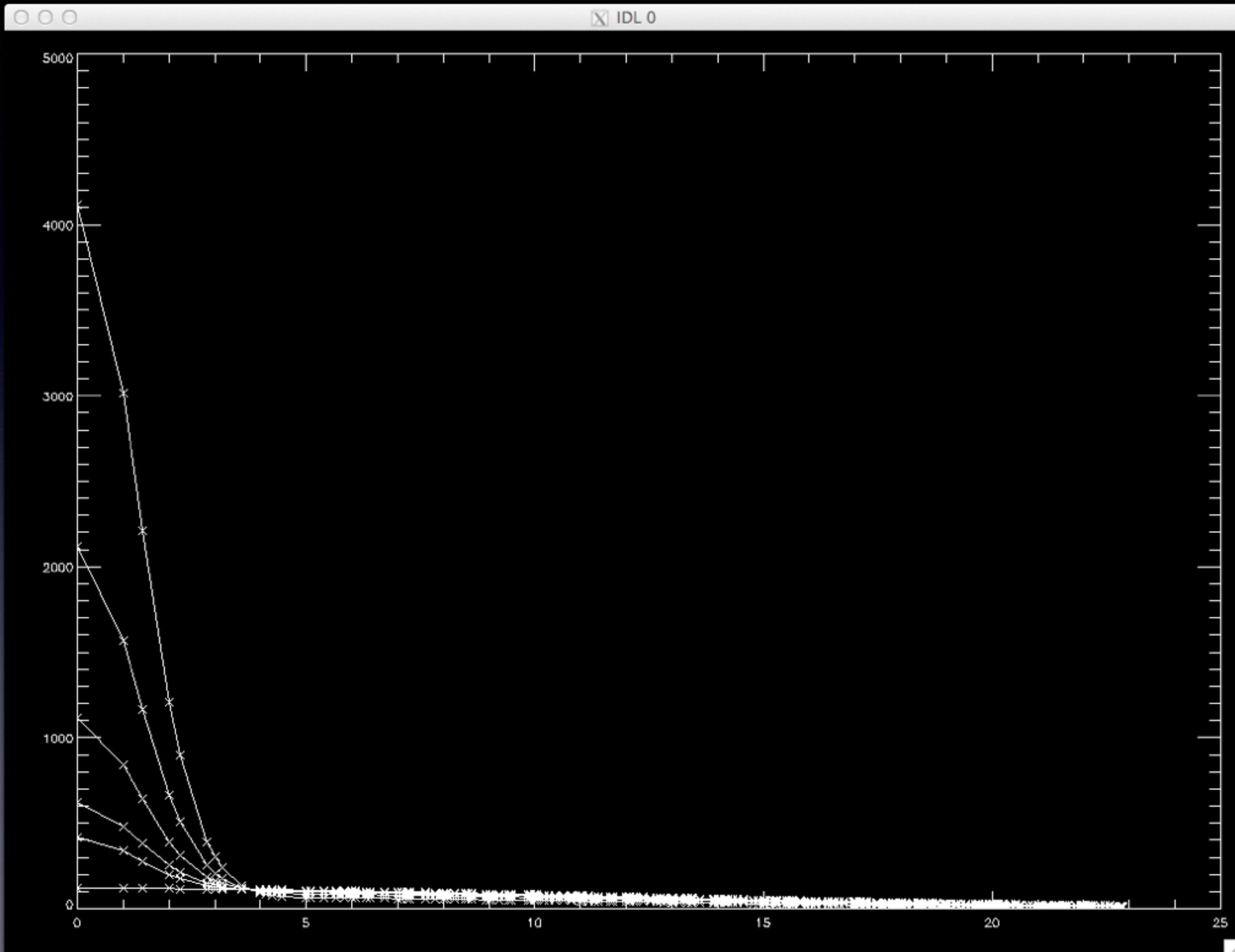
http://www.gemini.edu/sciops/instruments/gems/mcao-nutshell

http://www.gemini.edu/sciops/instruments/gems/introduction-gems

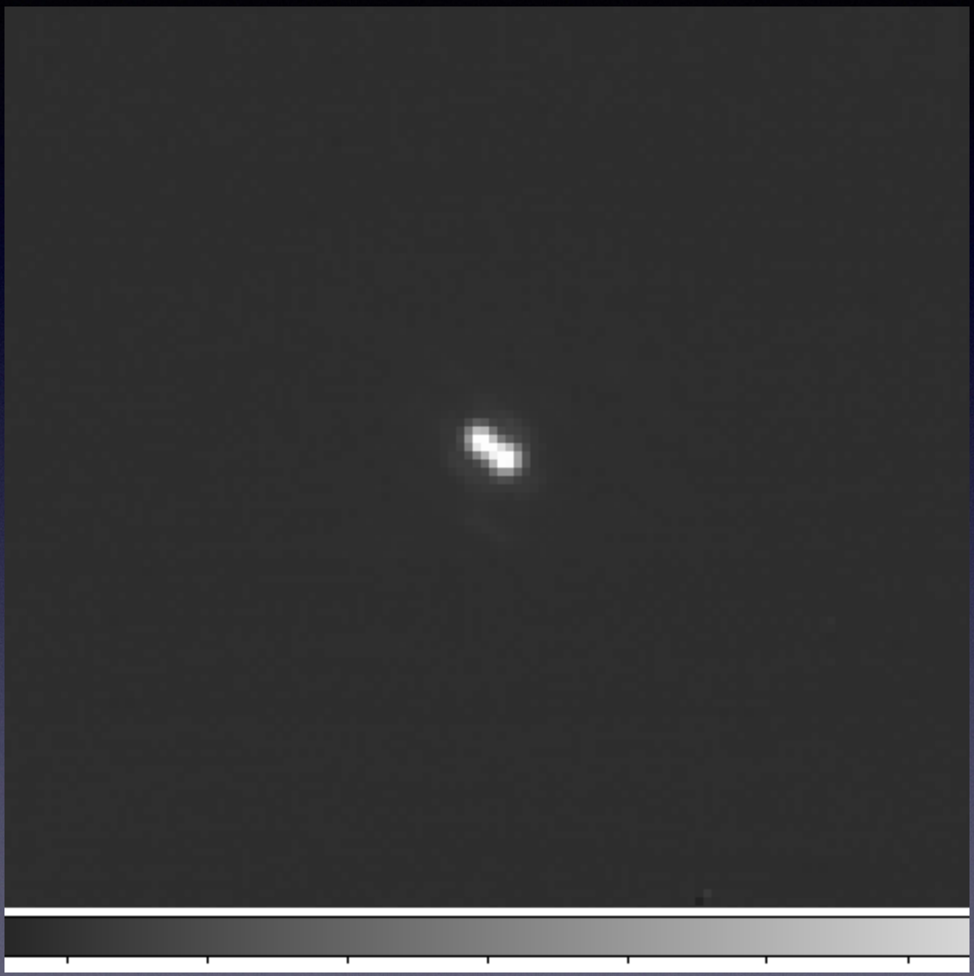

Photo: Tetsuharu Fuse © Subaru Telescope, NAOJ

# Simulated Data




IDL 0
5000
4000
3000
2000
1000
0
0
5
10
15
20
25

# Real Data

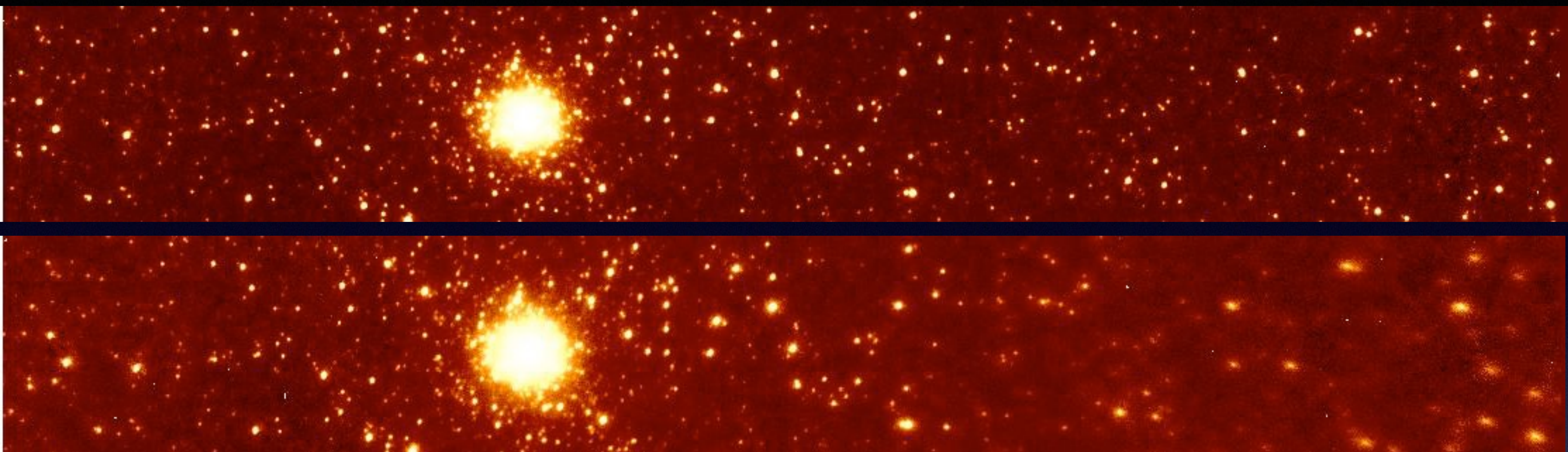


peak scaling linear

# Real Data

peak scaling log

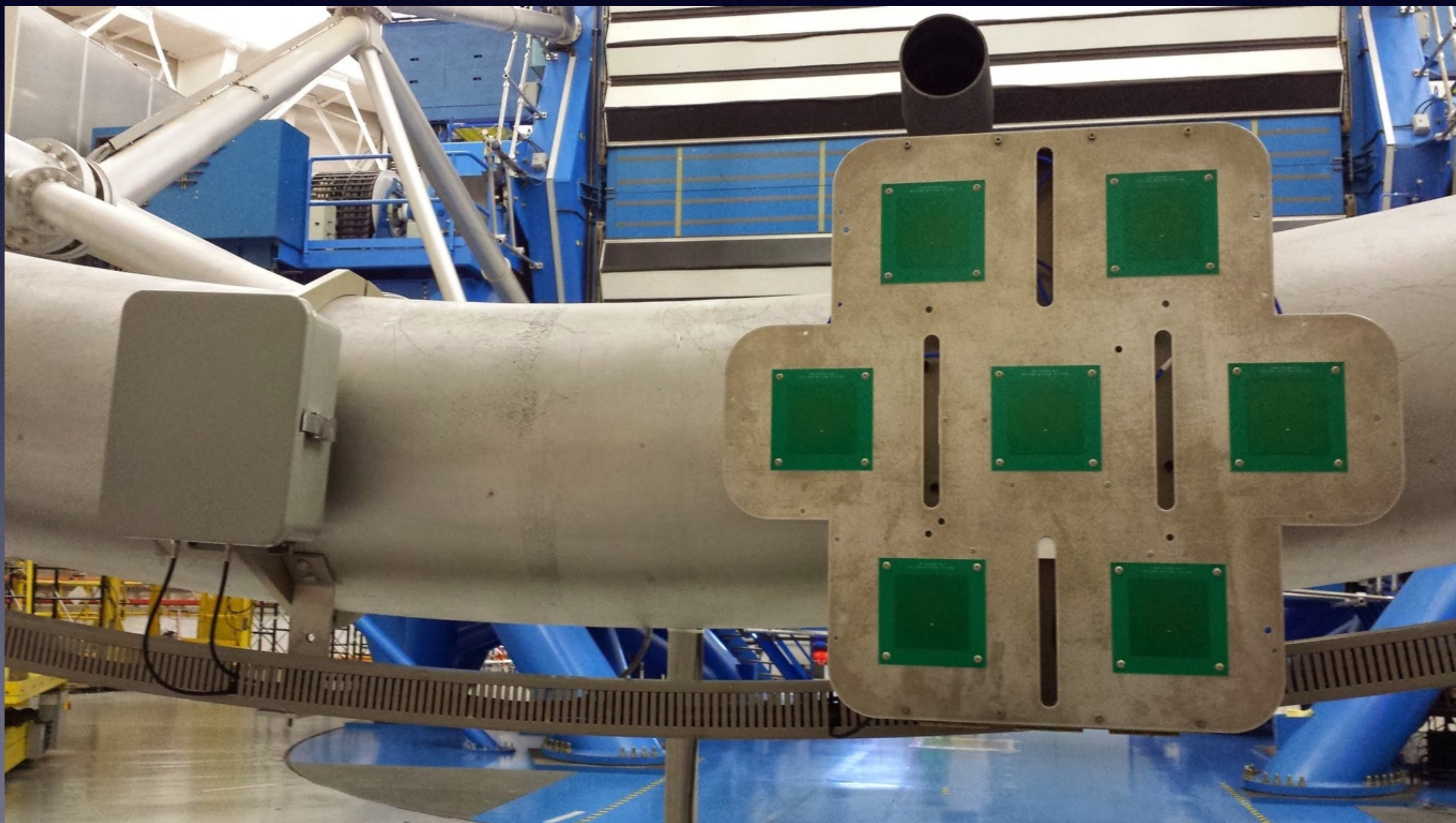
# Field Lens



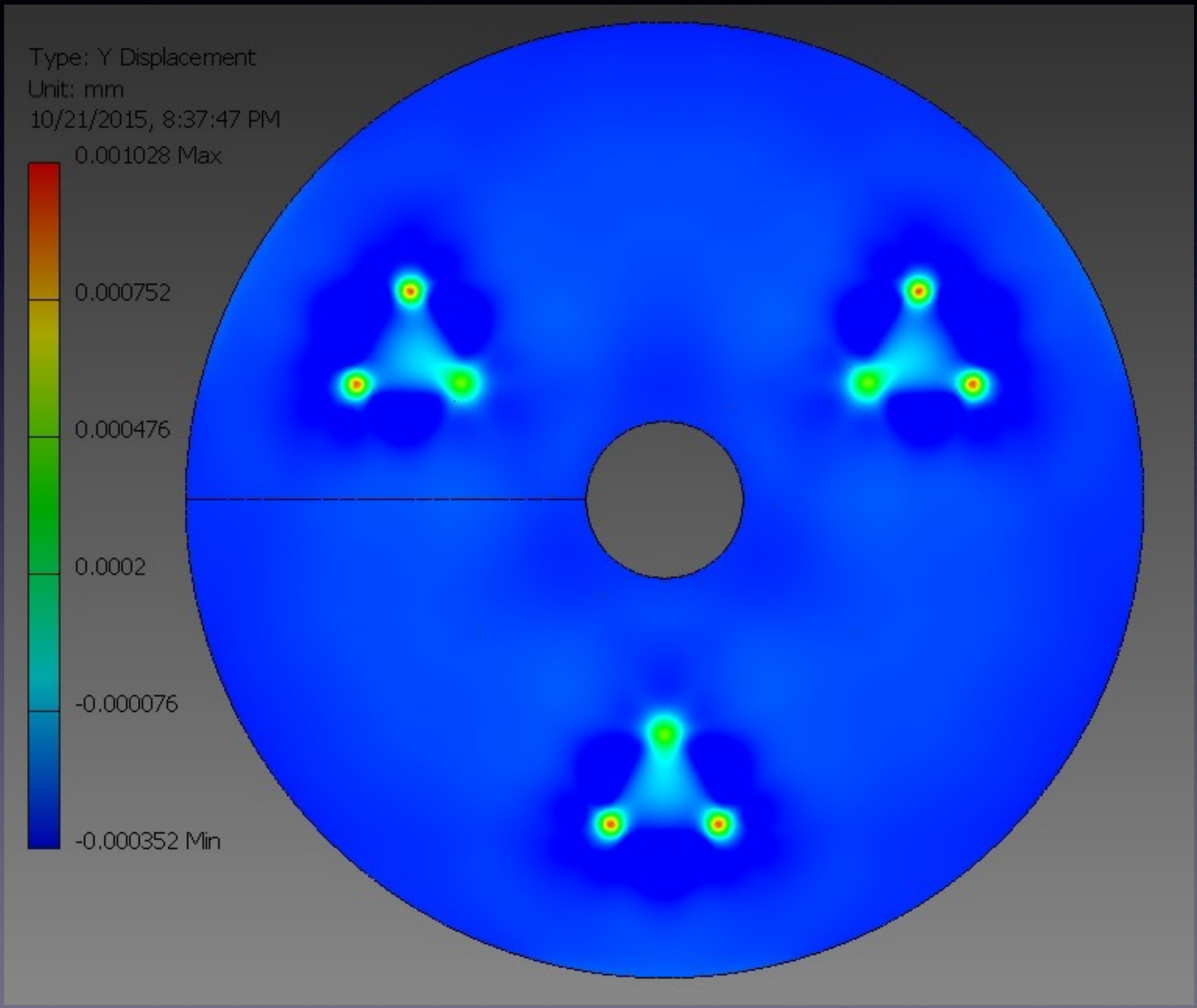
45 arcseconds (~900 pixels at f/14)

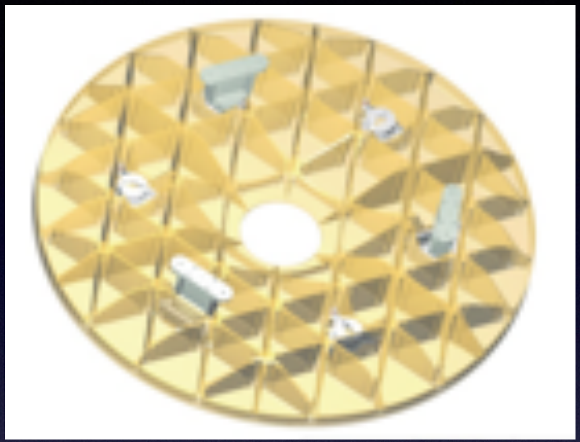
# Rapid Target of Opportunity Laser

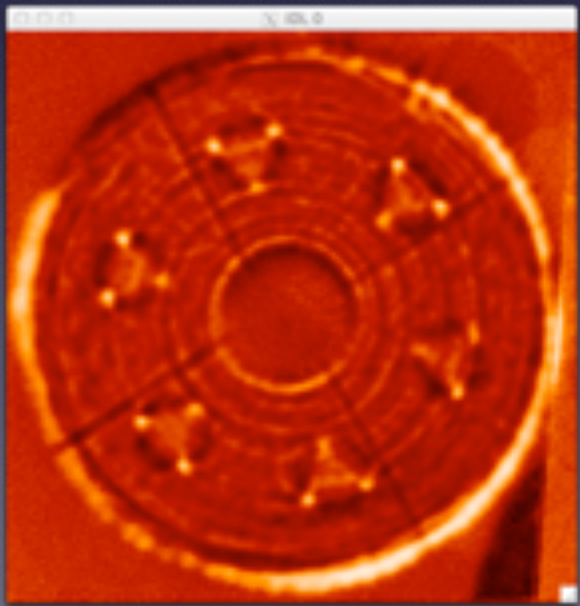
## Transponder-Based Aircraft Detection (TBAD)



# M2 Print-Through



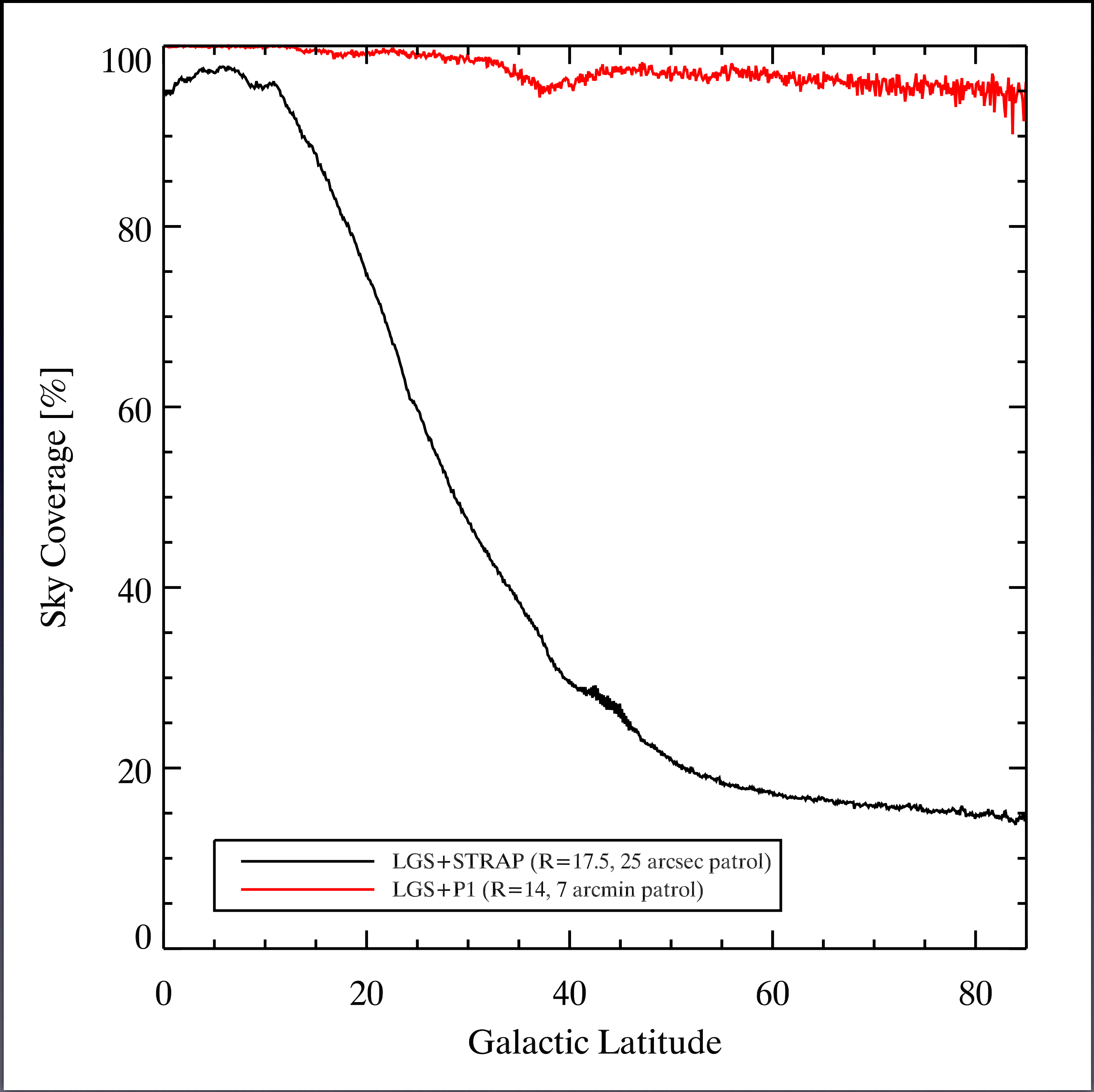



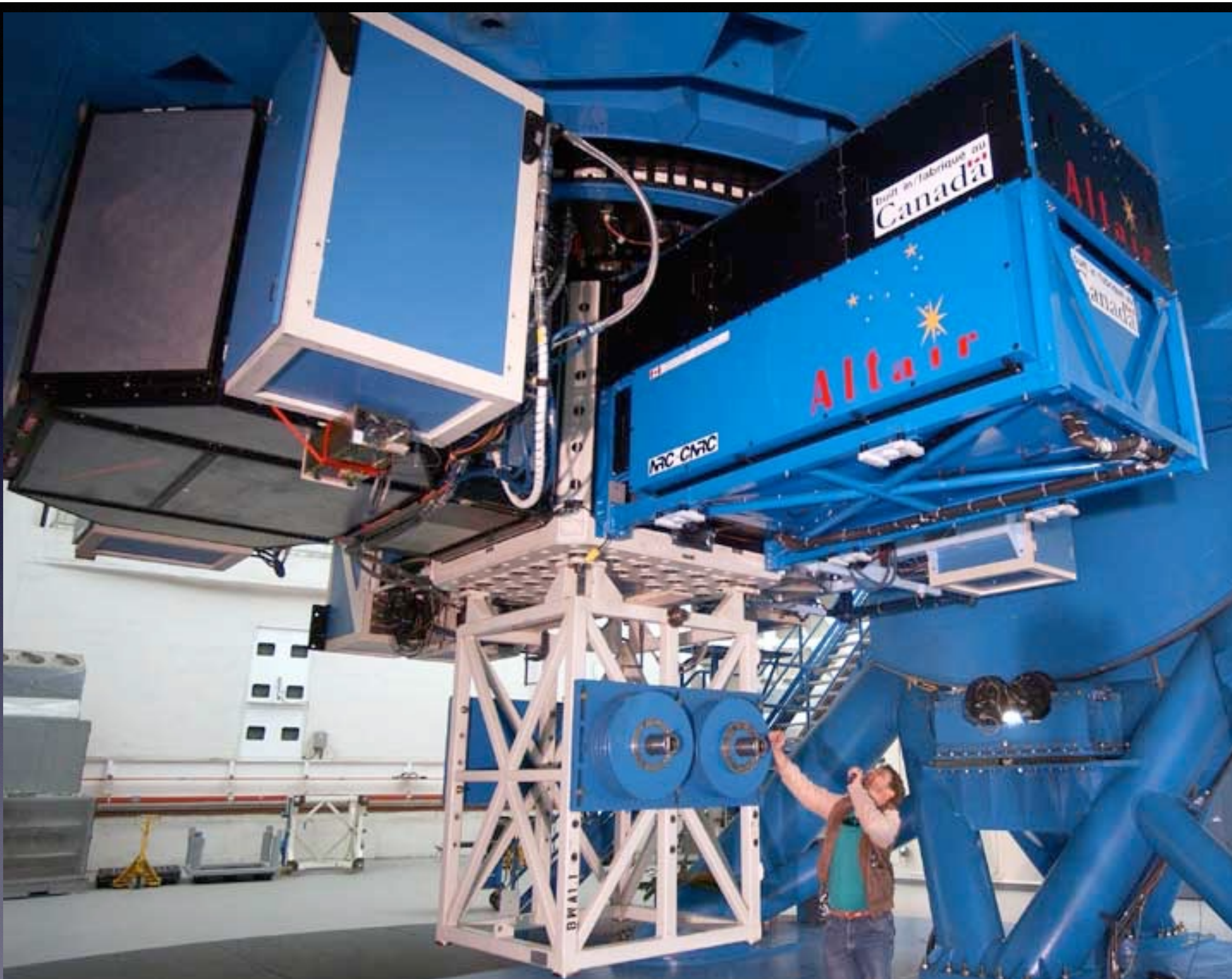


Altair Sky Coverage 95%

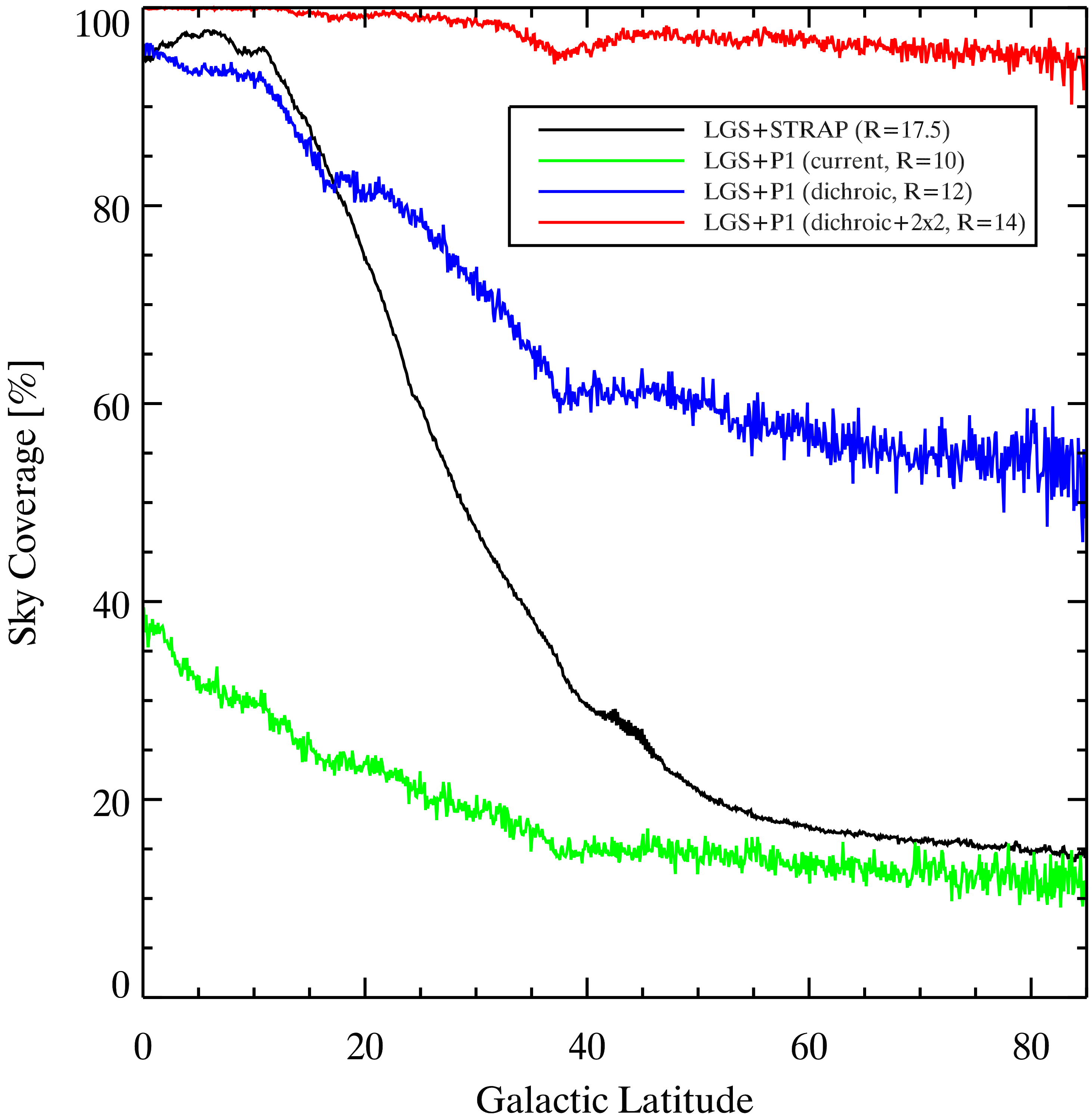
LGS and LGS+P1 "super-seeing" mode

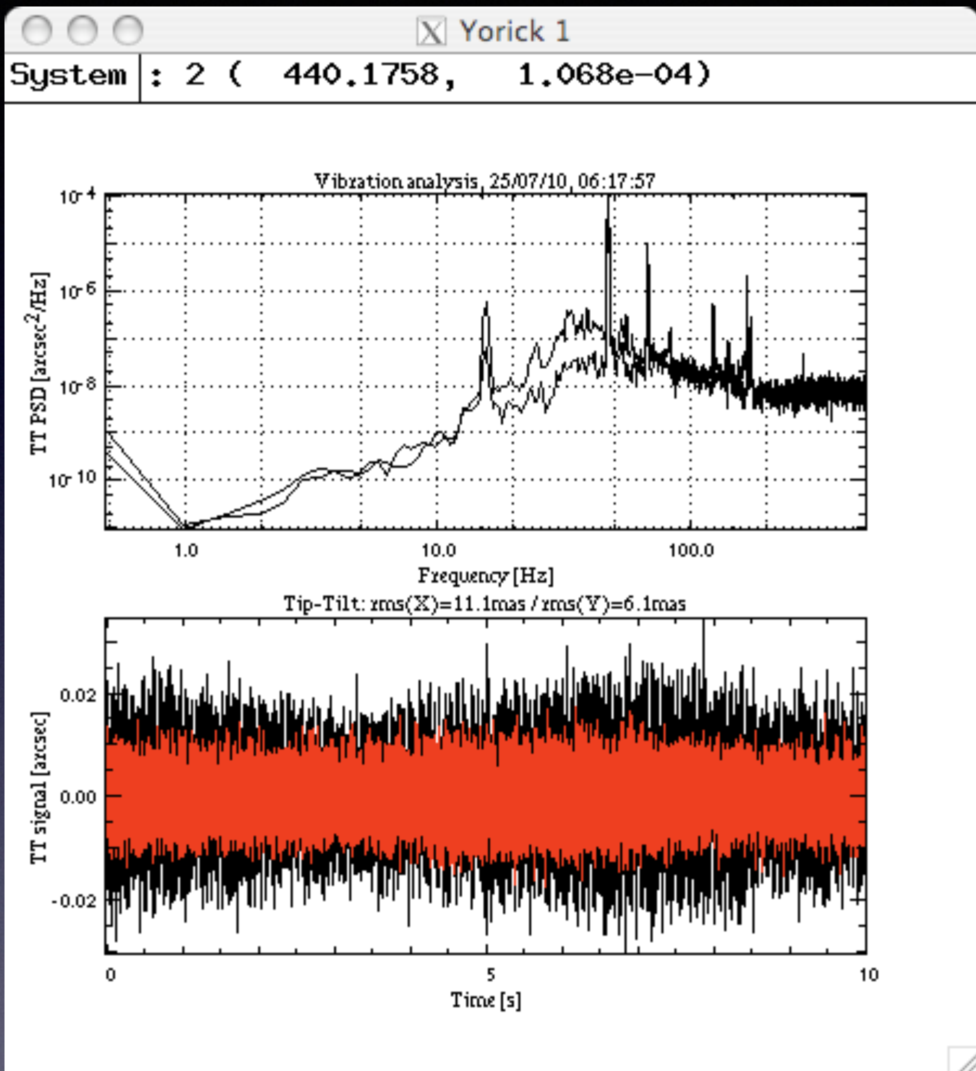
0.2" in K in 70%-ile seeing (0.55" natural)

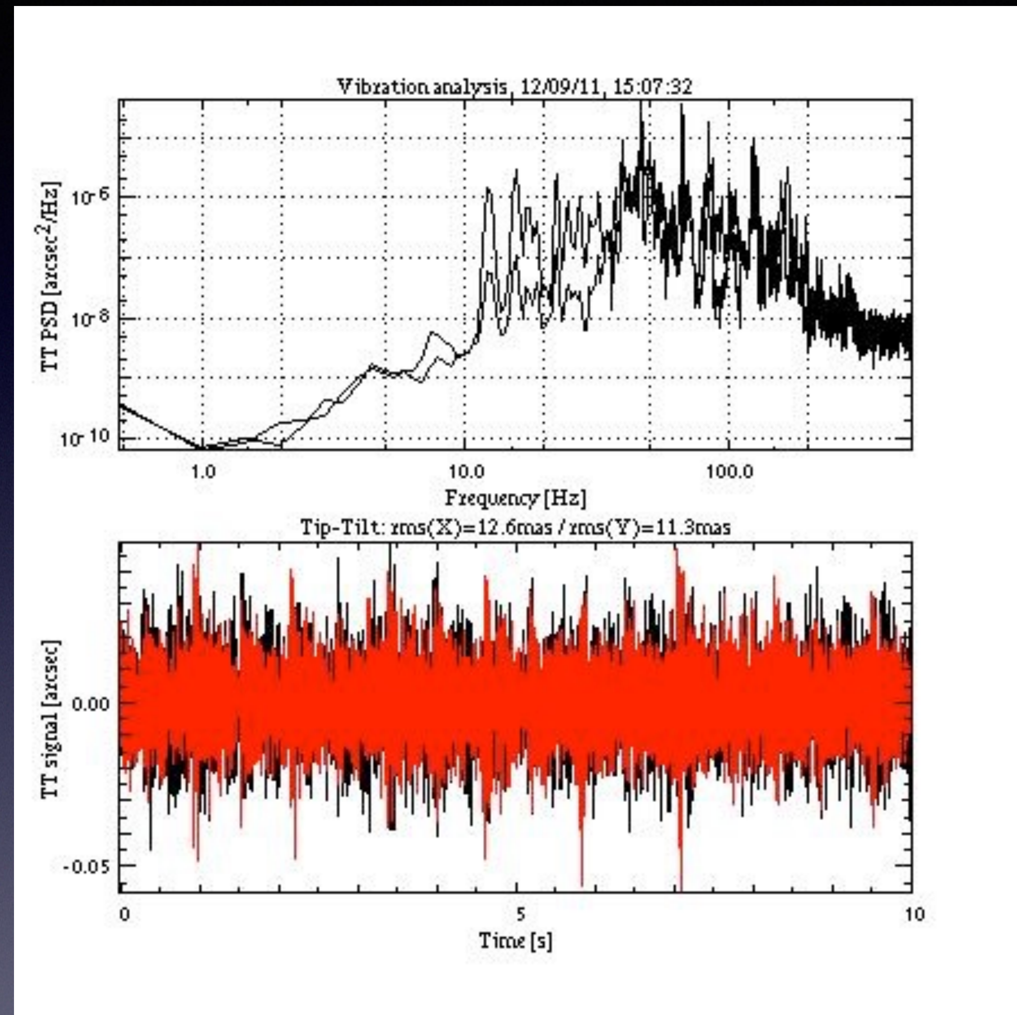


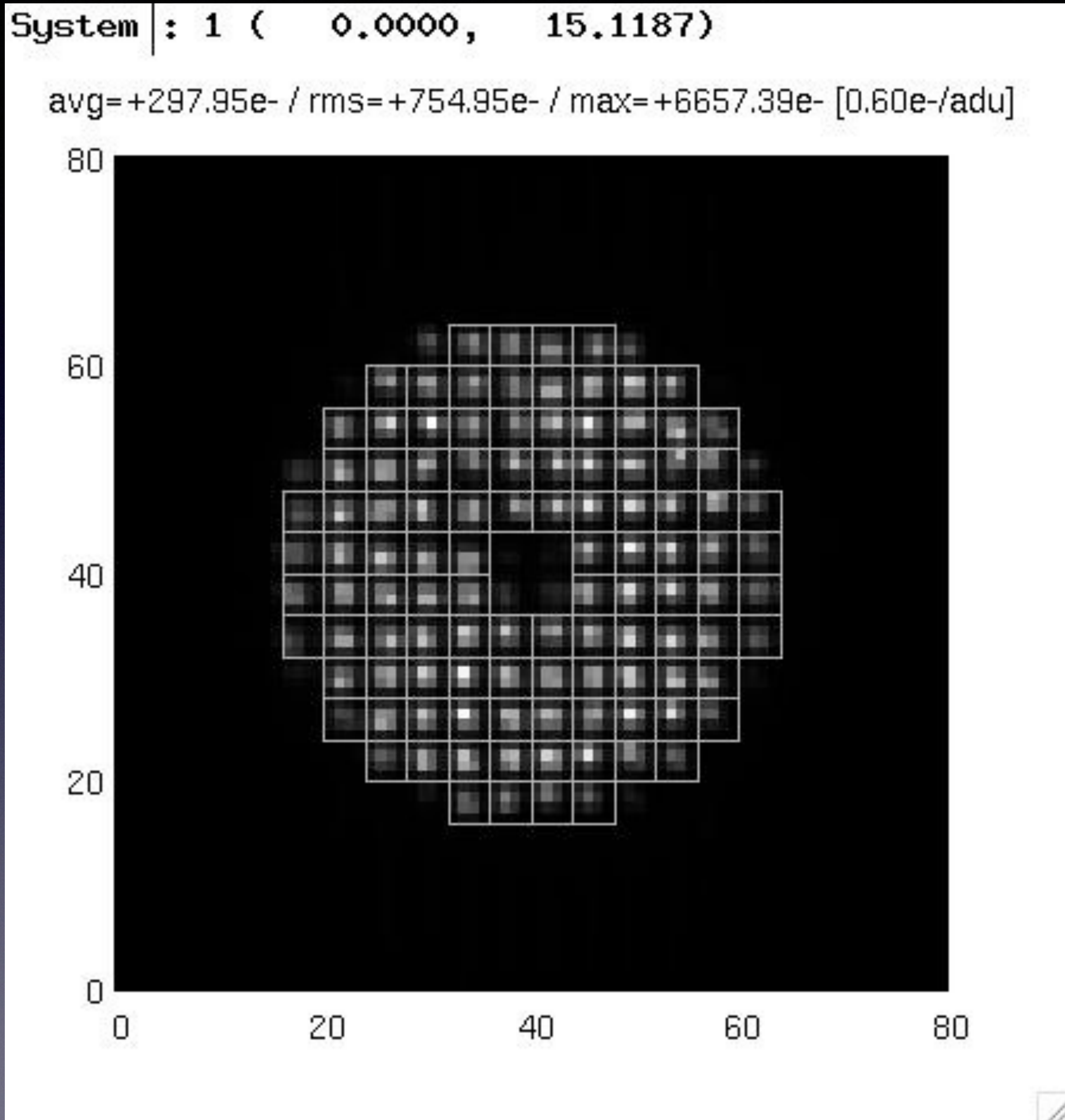

Built in/fabriqué au
Canada
Altair
NRC CNRC

Deformable mirror (left), beam splitter (center) and gimbal mirror (above right)


100
80
60
40
20
0
Sky Coverage [%]
0
20
40
60
80
Galactic Latitude
LGS+STRAP (R=17.5)
LGS+P1 (current, R=10)
LGS+P1 (dichroic, R=12)
LGS+P1 (dichroic+2x2, R=14)


Yorick 1
System : 2 ( 440.1758, 1.068e-04)
Vibration analysis, 25/07/10, 06:17:57
TT PSD [arcsec^2/Hz]
Frequency [Hz]
Tip-Tilt: rms(X)=11.1mas / rms(Y)=6.1mas
TT signal [arcsec]
Time [s]


Vibration analysis, 12/09/11, 15:07:32
TT PSD [arcsec^2/Hz]
Frequency [Hz]
Tip-Tilt: rms(X)=12.6mas / rms(Y)=11.3mas
TT signal [arcsec]
Time [s]


System : 1 (  0.0000,  15.1187)
avg=+297.95e- / rms=+754.95e- / max=+6657.39e- [0.60e-/adu]
80
60
40
20
0
0
20
40
60
80

# GeMS Commissioning

March - May 2011

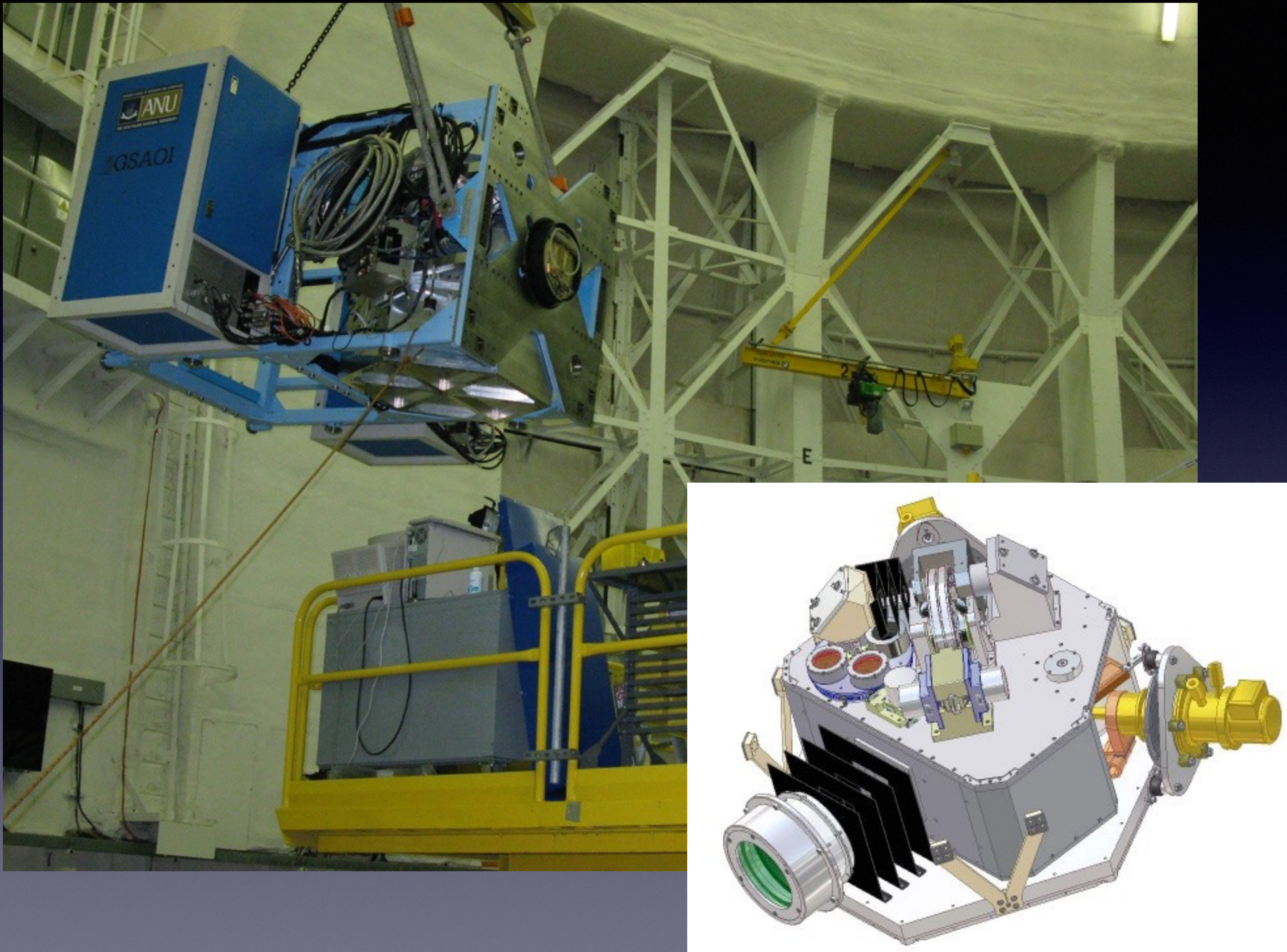
# GeMS: What is it?

- GeMS = Gemini MCAO System
- MCAO = Multi-Conjugate Adaptive Optics
- GeMS = Laser + BTO + LLT + GSAOI + Canopus
- GSAOI = Gemini Adaptive Optics Imager
- Canopus = the Adaptive Optics system itself
- Extensive Canopus Documents are at

  http://myst.cl.gemini.edu/twiki/bin/view/MCAO/WebHome

# Meet GSAOI

- GSAOI is the science camera for GeMS
- Consists of four 2k x 2k chips in a square
- Provides a 85” x 85” field of view with a plate scale of 20 mas / pixel
- Designed to Receive the f/32 output from Canopus, not the f/16 beam from the telescope!
- There are 4 On Detector Guide Windows (ODGW) that can act as Tip/Tilt Guide Stars (TTGS)


ANU
GSAOI
E

# Meet Canopus

- Canopus is the Adaptive Optics instrument itself
- Canopus sits on the AO port just like Altair and uses the AO fold just like Altair, except that it delivers an f/32 beam, not an f/16 beam
- Canopus has 3 Deformable Mirrors (DMs).
- The DMs are conjugated to 0 km (240 actuators), 4.5 km (324 actuators), 9 km (120 actuators). This is the Multiconjugate part.
- There is one Tip/Tilt Mirror (TTM) and one Slow Focus Sensor (SFS), similar to Altair

# Meet Canopus

- Canopus has 3 Pyramid style Tip Tilt Guide Star WaveFront Sensors (TTGS WFS)

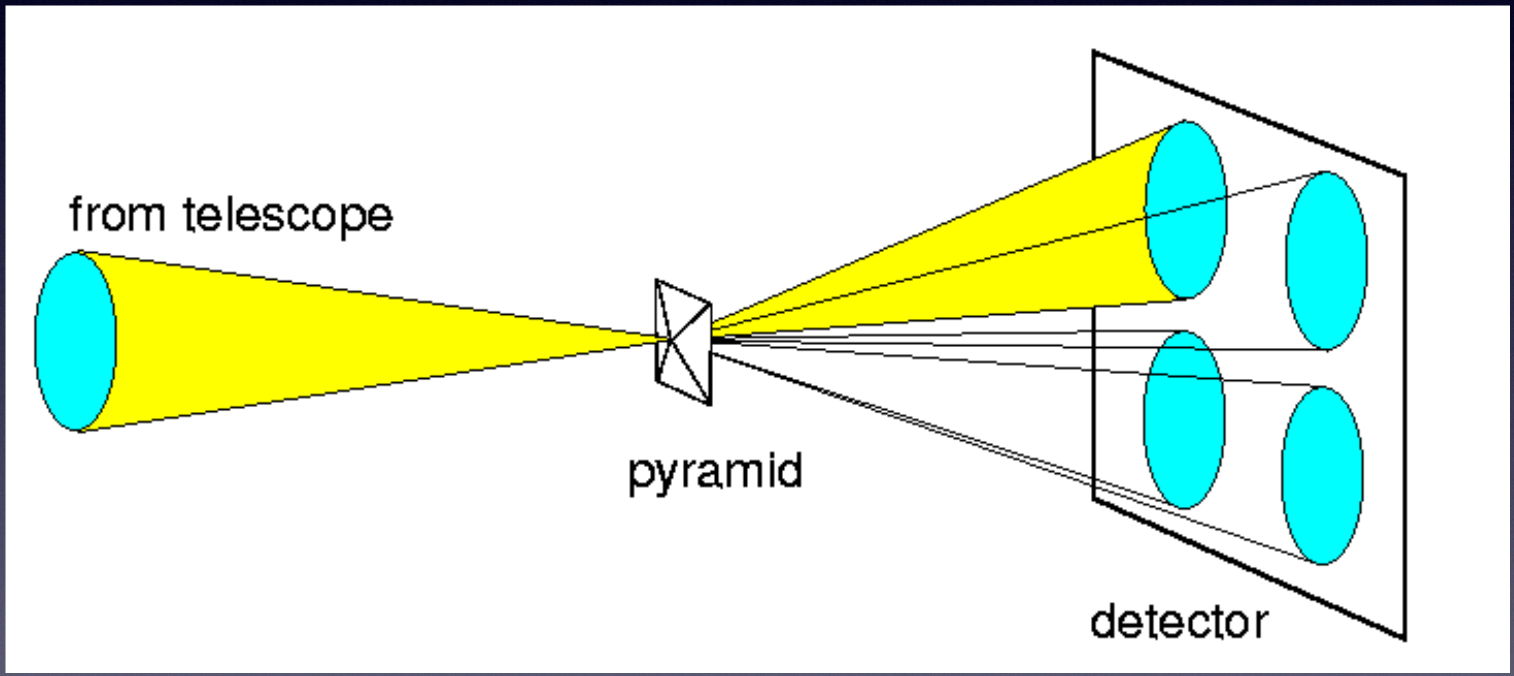
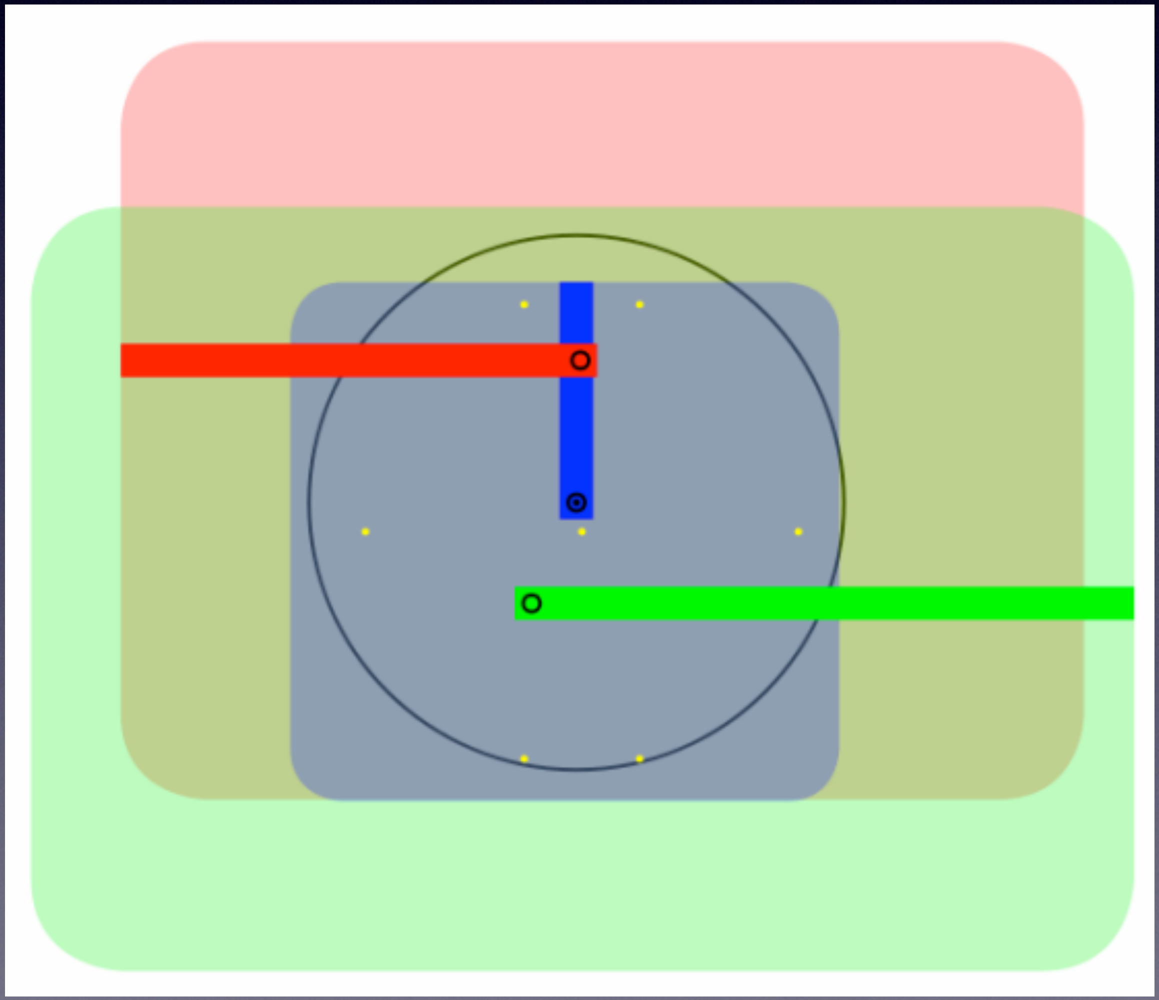



Image credit: Dr. Andrei A. Tokovinin
http://www.davincisworld.com/Light/AOtutorial.htm

# Meet Canopus

- Two of the WFS (c1 and c2) positioners ride on the third WFS (c3). Why?



# Meet the Commissioning Team

- AO: François, Benoit, Jean-Pierre Veran (HIA), Brent Ellerbroek (TMT), Damien Gratadour (Paris/Meudon)
- SysEng: Gelys
- SW: Matthieu, Javier, Cristian Urrutia
- Laser/BTO: Maxime, Celine, Vincent, Tomislav, Sarah Diggs, Claudio Marchant
- SSAs: Ariel, Andrew, Eduardo, Tony
- GSAOI: Michelle, Rodrigo, Peter McGregor, Peter Young, J. Van
- Spotters: Rodrigo Balladares, Carlos Segura, Camila Duran, Eric Petit, P. Veliz
- Electronics: Vanessa Montes, Ramon Galvez, Eduardo Tapia
- Others: Markus, Callie, Chris Morrison, Bryan Miller, Nancy, Doug, Gustavo, Felipe Colazo, Lucia, John Michael Plaza
- Astronomer: Me
- And many, many others (this is not a complete list)!

# Meet the Comissioning Team


Jan 2011

# Meet the Commissioning Team

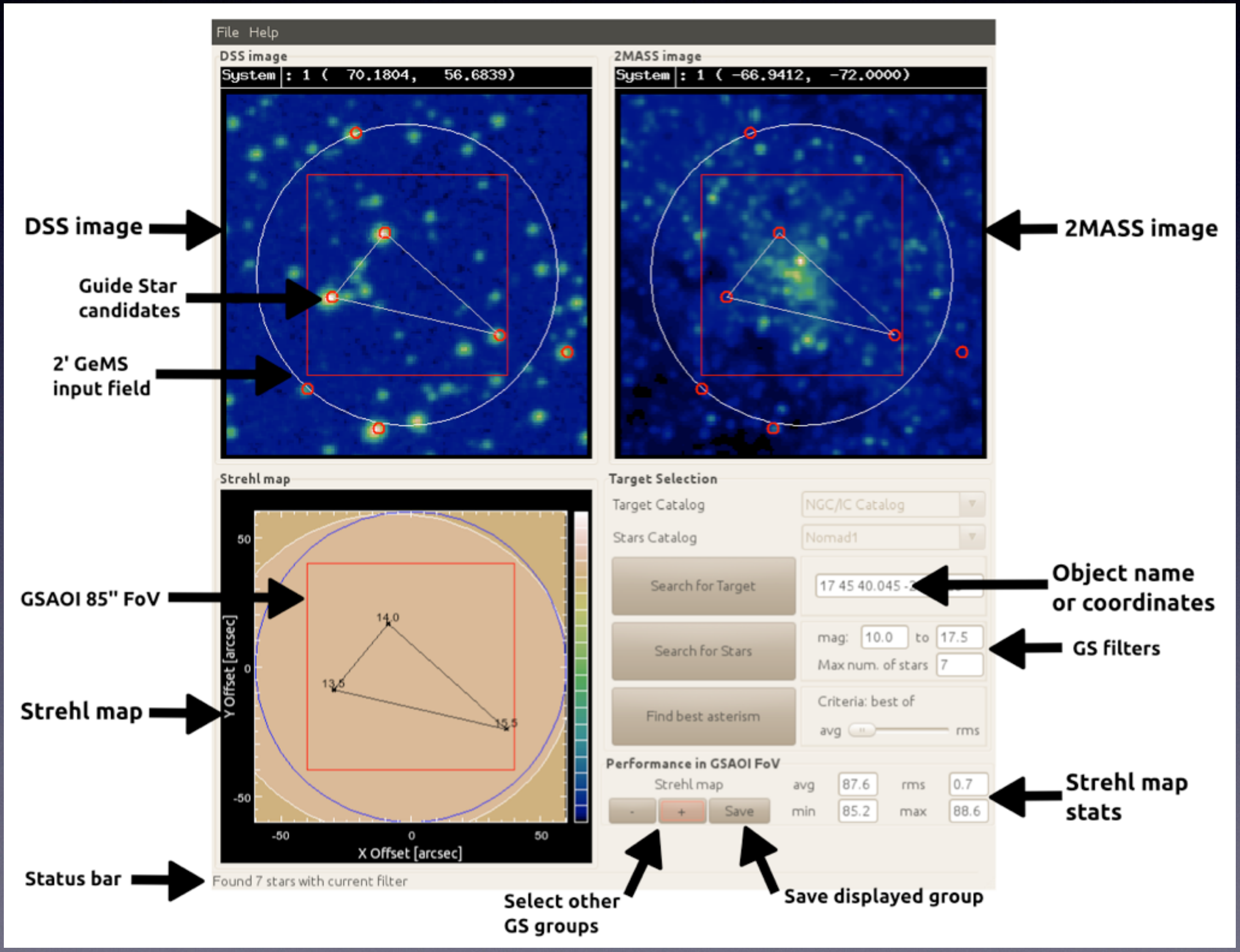
April 22, 2011 (last night of run)

# GeMS WFSs

- There are more GeMS WFSs that will be used for science operations than currently in all the other instrumentation at Gemini North and South combined!
- GeMS (13)
  - Canopus: 5 Laser, 3 TTGS, 1 SFS
  - GSAOI: 4 ODGW
- GN (6)
  - Altair (4): NGS, LGS, SFO, STRAP; P2 (1); GMOS OIWFS (1)
- GS (4)
  - NICI NGS (1), P1 (1), P2 (1), GMOS OIWFS (1)
- Not currently used for science (4)
  - HRWFS (2), NIRI OWFS (1), NIFS OIWFS (1), GNIRS OIWFS (1)
- What does this mean? Probe Mapping!

# GeMS Operations

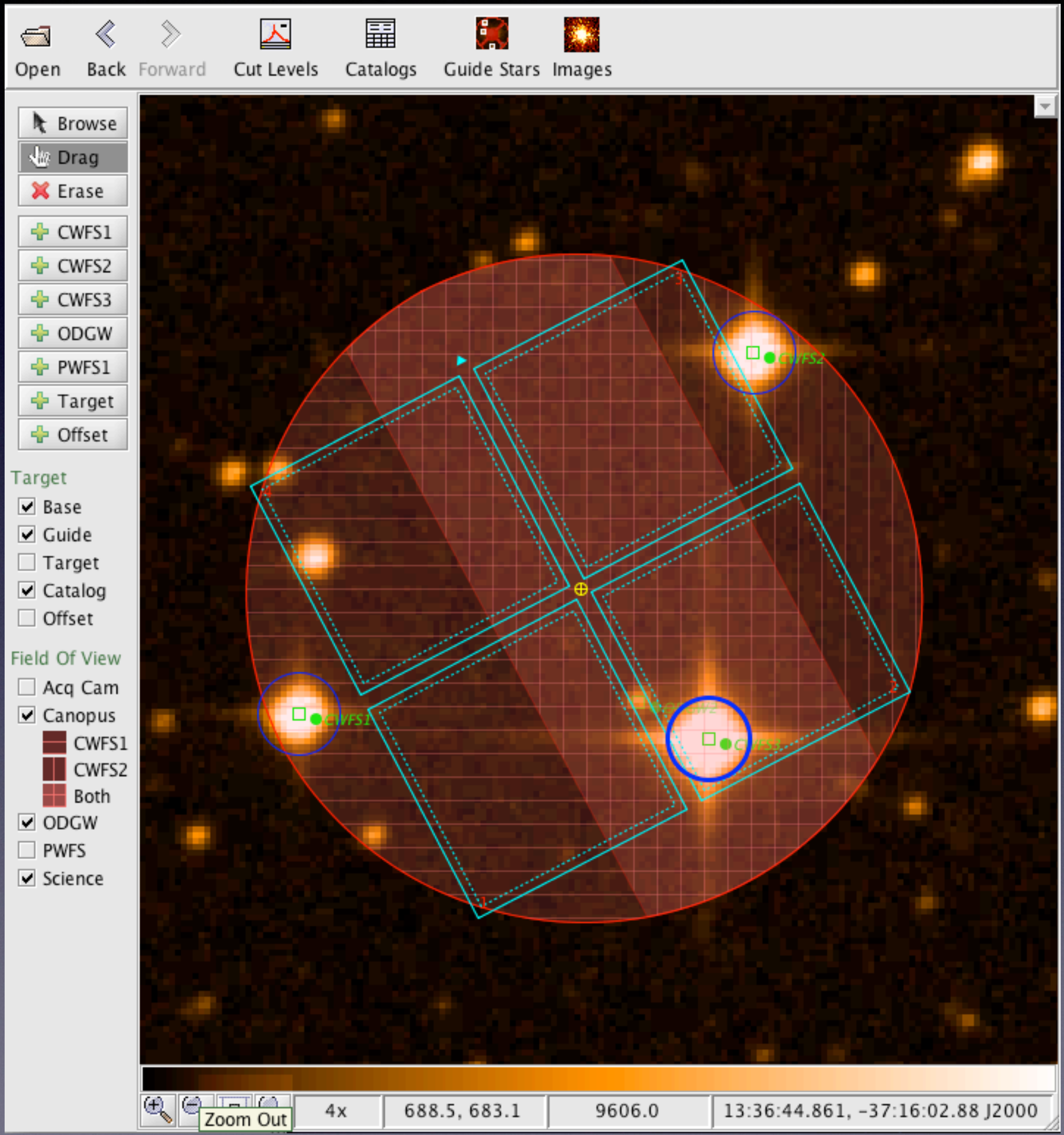
- "Mascot" is a user tool for finding guide stars



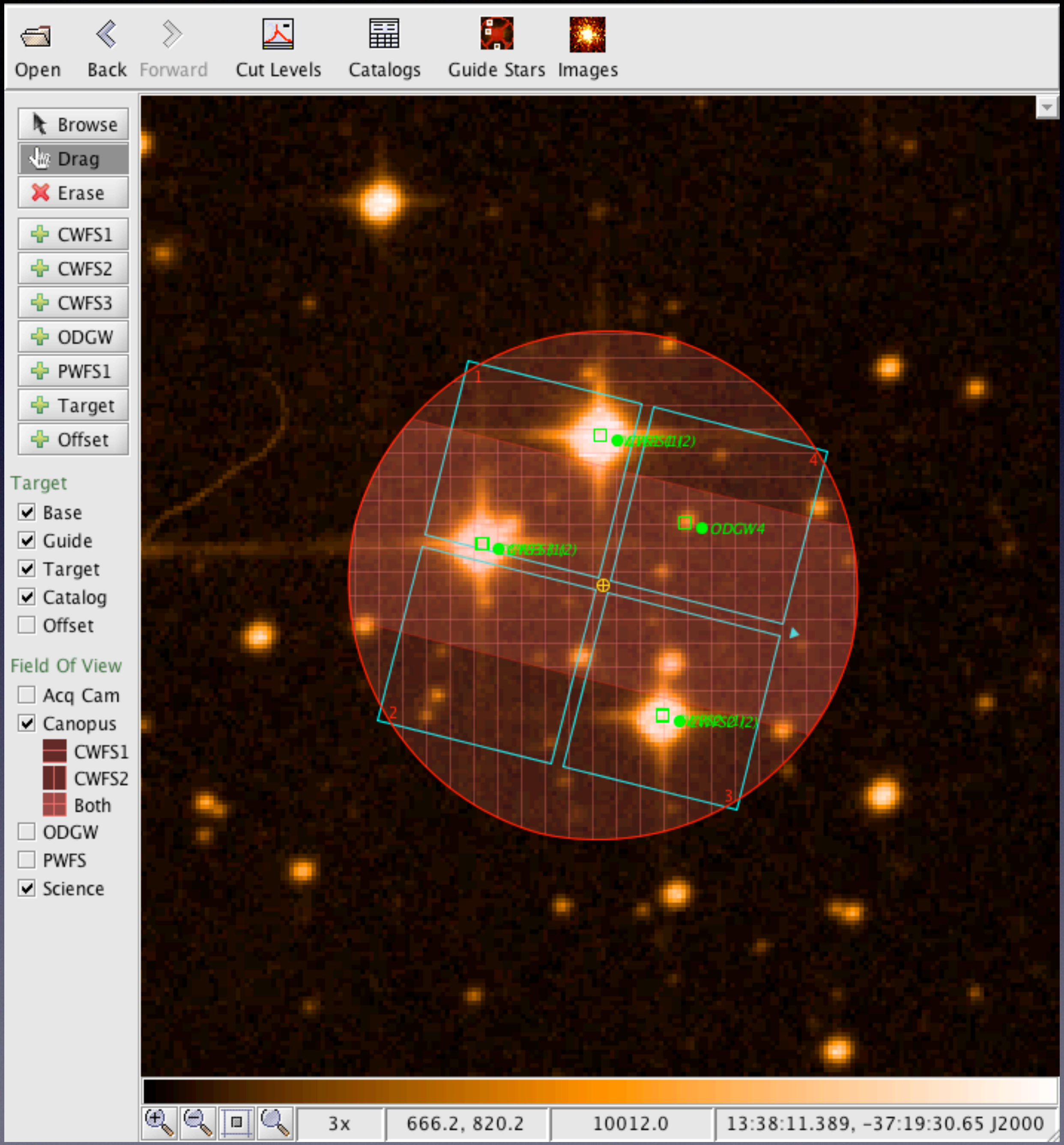
# GeMS Operations

- Once your field is selected, Observing Tool (OT) setup is next
- The OT interface is very good
  - Canopus TTGS patrol region is updated based on offset iterators and Position Angle
  - Canopus TTGS complexity will be properly handled in terms of orientation and c1/2 riding on c3 (minor issues remain in size of patrol region)
  - GSAOI chips are correctly labelled and oriented
  - GSAOI ODGWs and Canopus TTGS are handled in a similar way to guide star selection

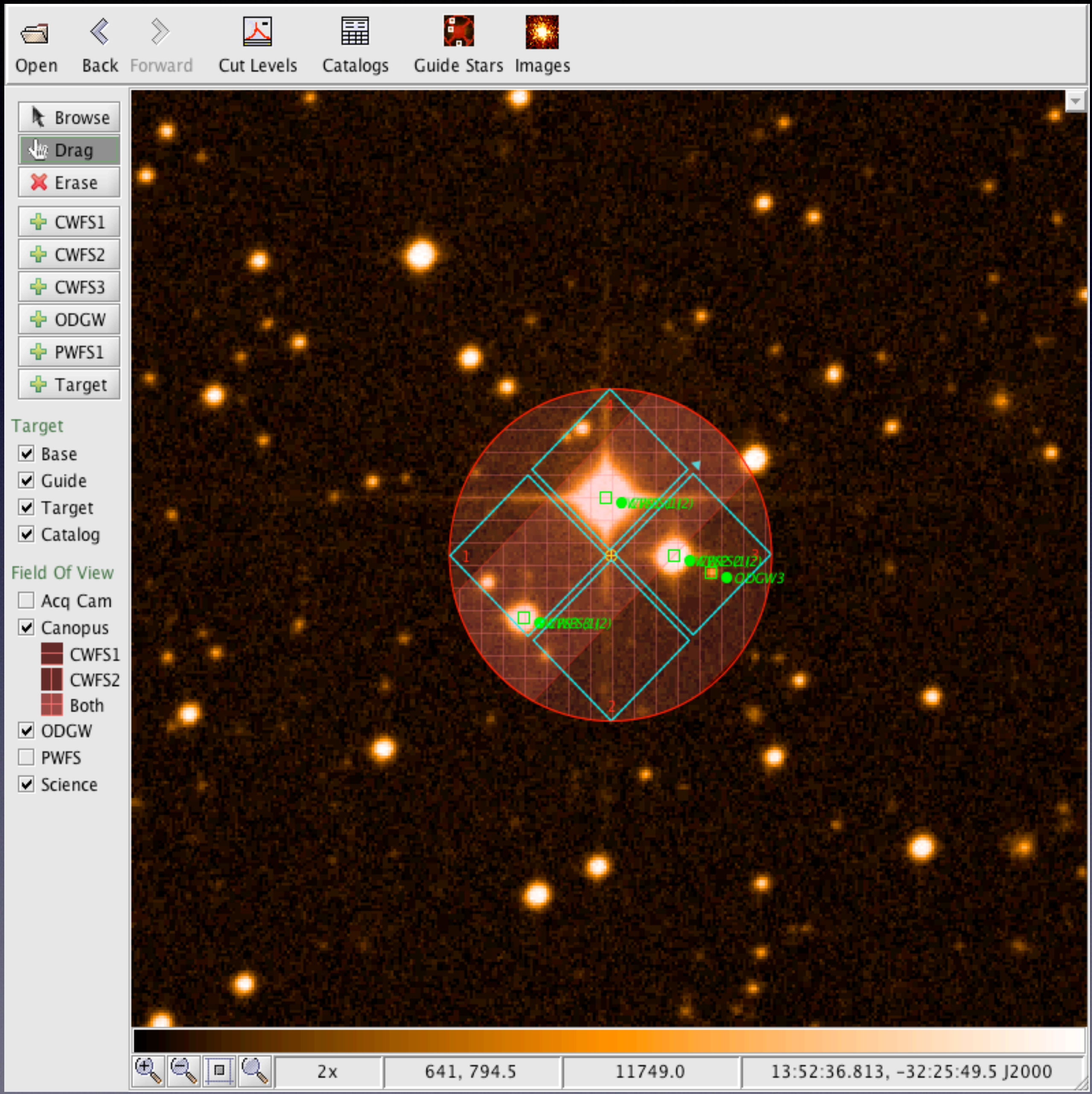
# GeMS Operations



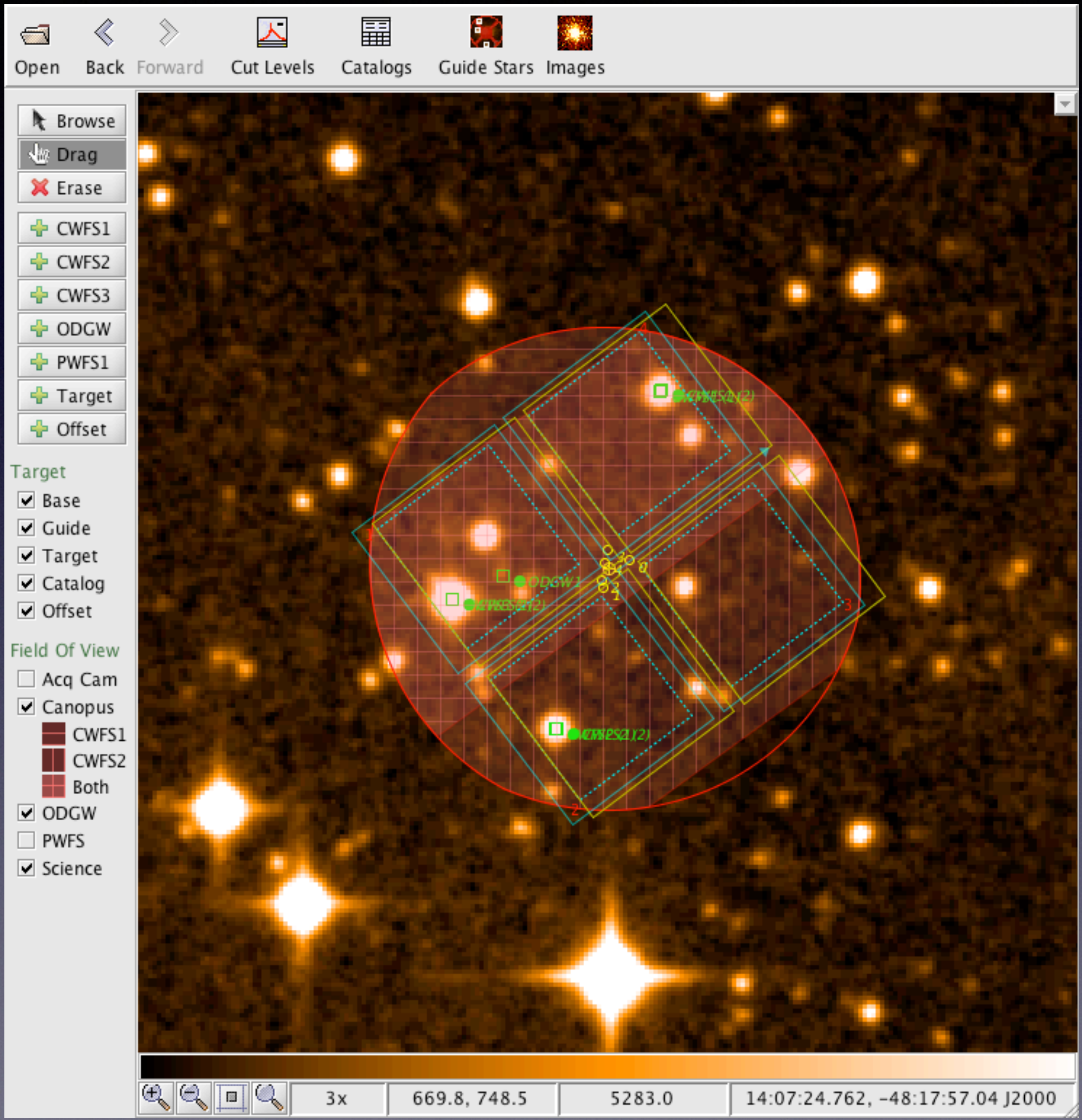
# GeMS Operations



# GeMS Operations



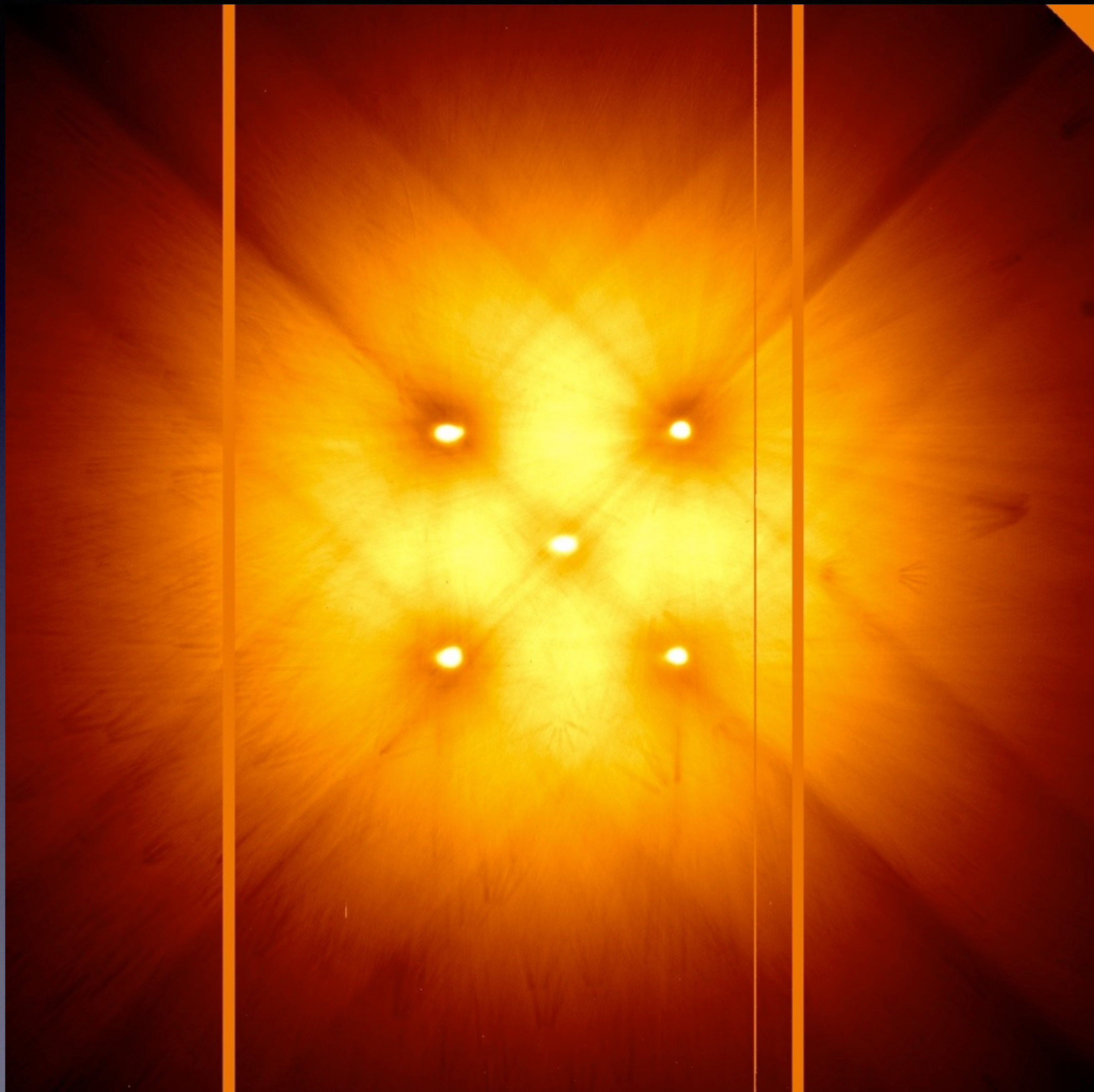
# GeMS Operations



# GeMS Operations

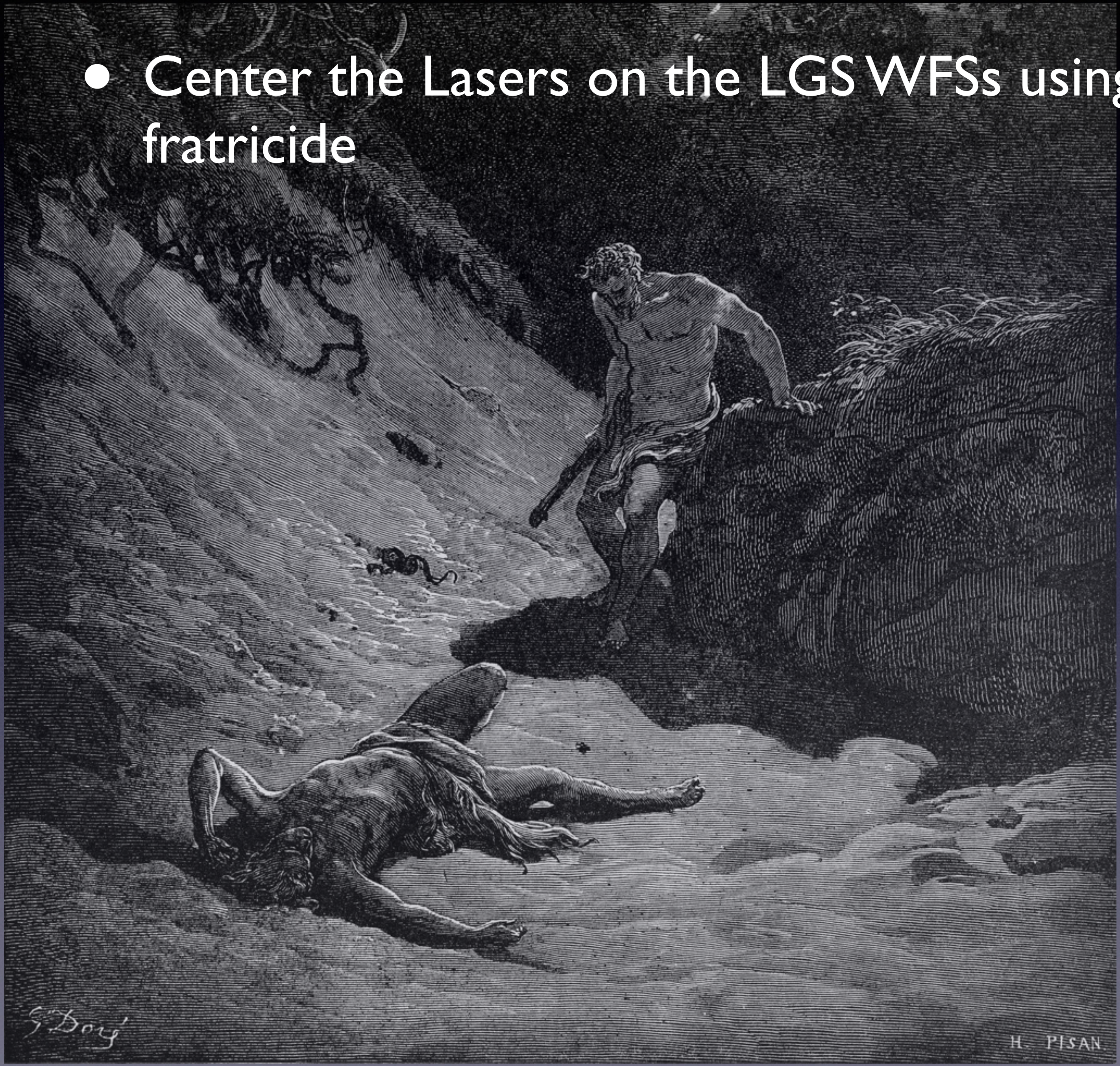
- Slew to target
- Check Laser Clearing House (LCH) clearance
- Check for clearance from aircraft spotters
    - There are many aircraft at GS!
- Propagate lasers (5 x 10 Watts)
- Roughly put lasers in correct position using the AC
    - This step is harder at GS because of Rayleigh

# GeMS Operations



# GeMS Operations

- Center the Lasers on the LGS WFSs using fratricide

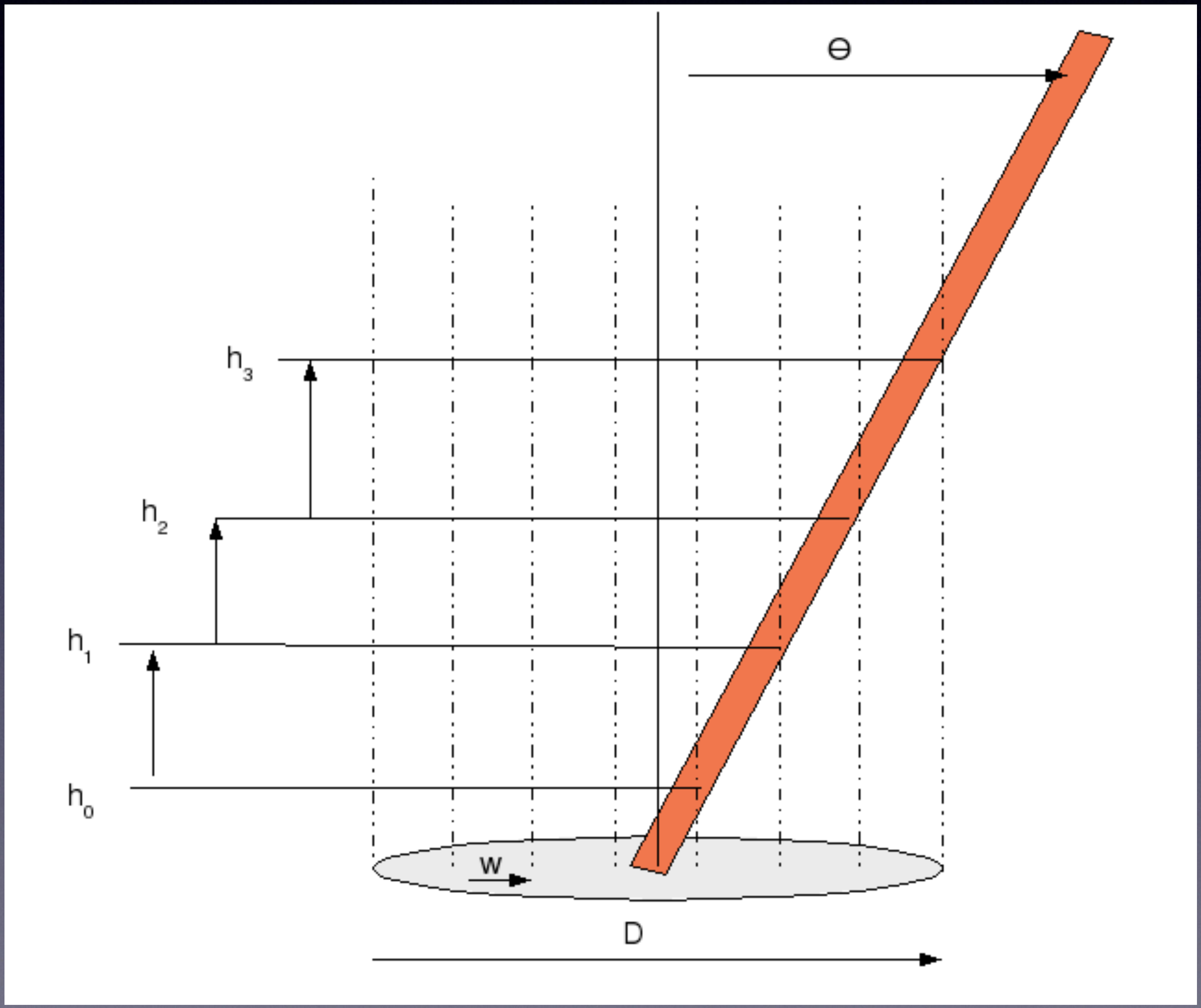


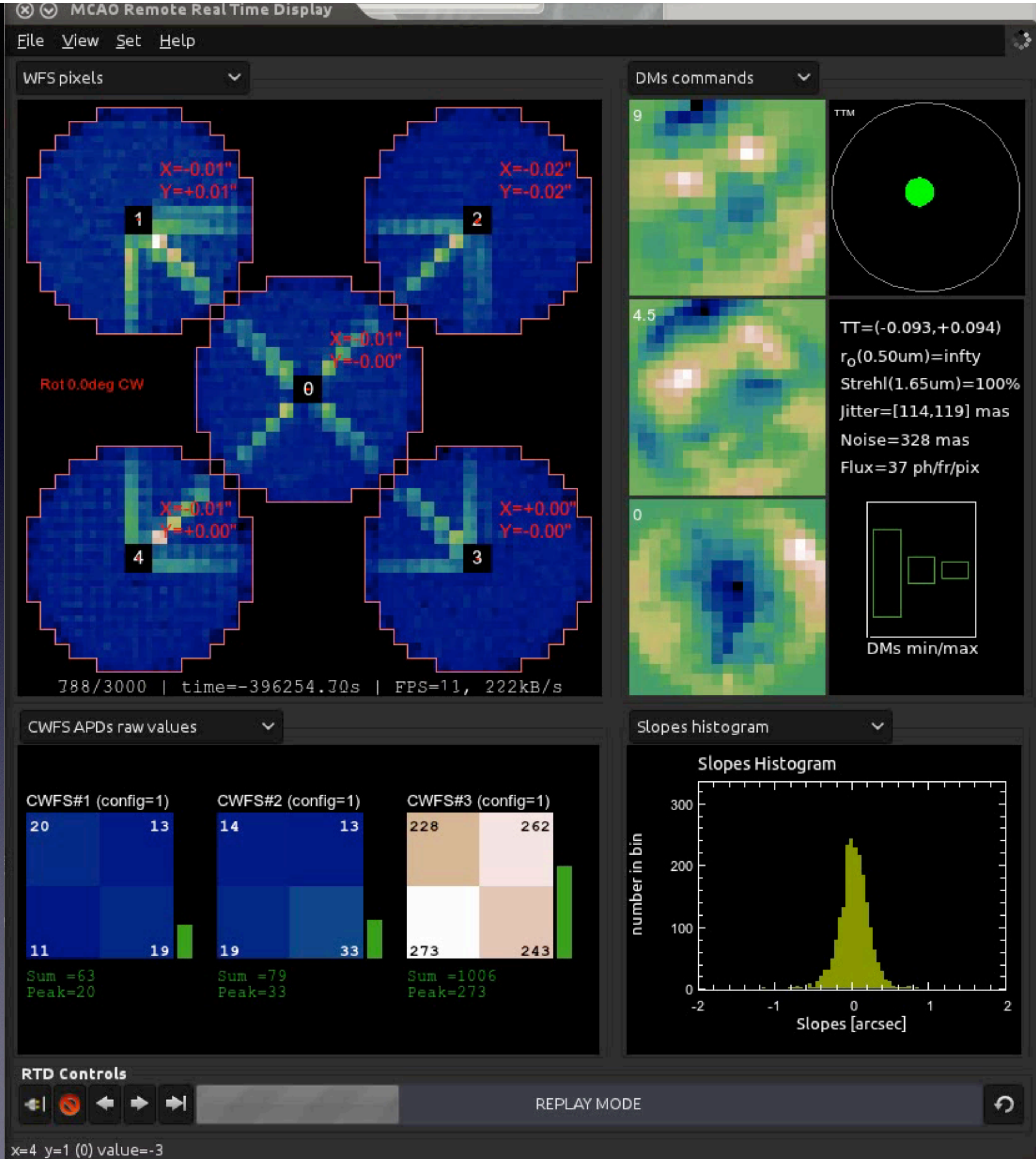
# GeMS Operations

- What is fratricide?
- From the MCAO blog (Benoit)
  - Wang et al. JOSAA 2010: "When the laser beam passes through the atmosphere, it will experience scattering and absorption that reduce its intensity as it propagates through the medium. Some fraction of the light lost due to scattering will be back scattered in the direction of the transmitter. In a LGS MCAO system [...], a fraction of the back-scattered light from each of the laser beams ends up being collected by WFSs observing the other LGSs. This effect is generally referred to as the fratricide effect. The fratricide effect is prominent mostly for MCAO systems that launch all the laser beams from near the center of the primary mirror (e.g., behind the secondary mirror). The effect is also stronger at higher zenith angles."

# GeMS Operations

- What is fratricide?



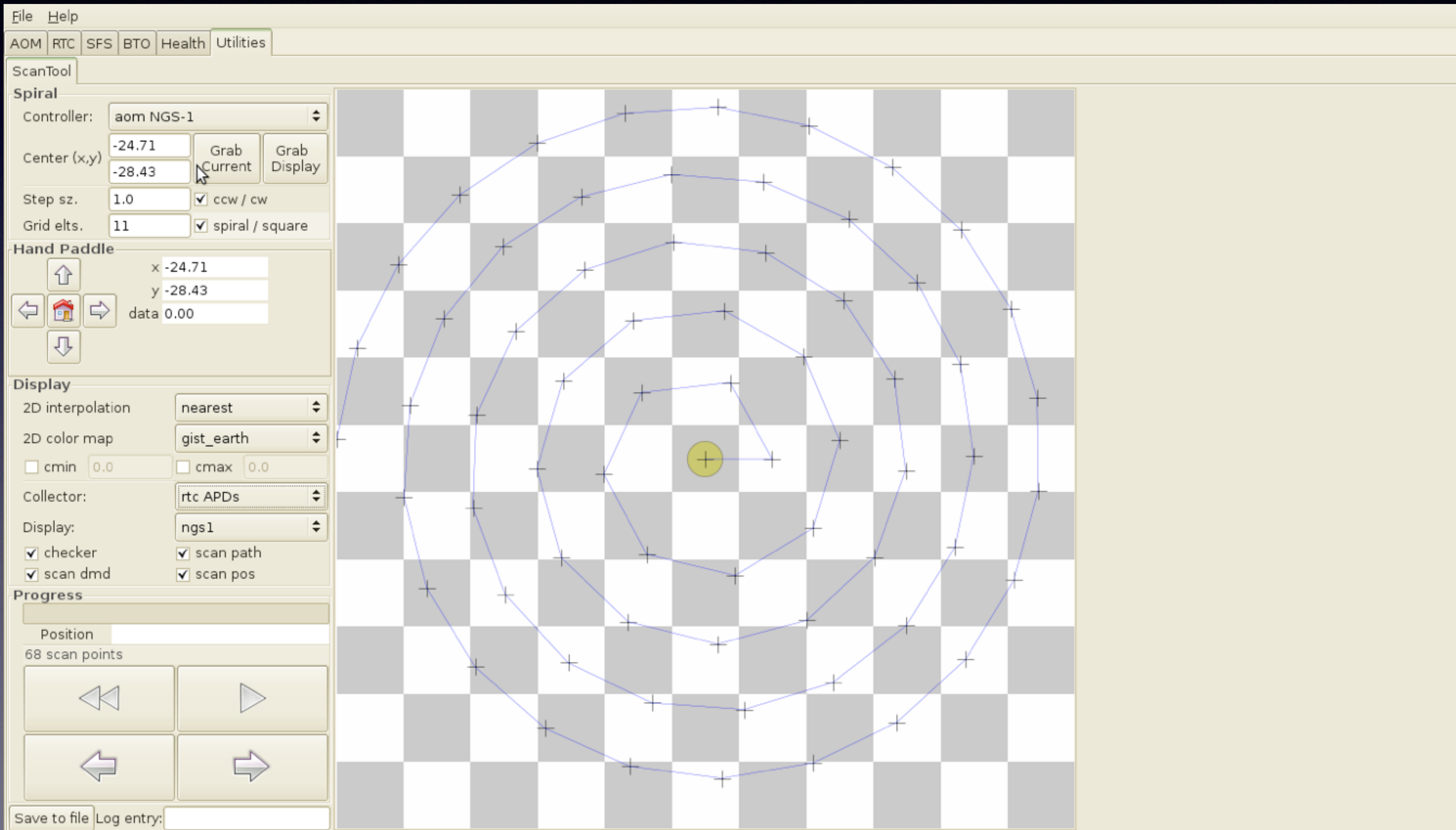

MCAO Remote Real Time Display
File View Set Help
WFS pixels
DMs commands
X=-0.01"
Y=+0.01"
X=-0.02"
Y=-0.02"
X=-0.01"
Y=-0.00"
Rot 0.0deg CW
X=-0.01"
Y=+0.00"
X=+0.00"
Y=-0.00"
1
2
0
4
3
788/3000 | time=-396254.70s | FPS=11, 222kB/s
9
4.5
0
TTM
TT=(-0.093,+0.094)
$r_0$(0.50um)=infty
Strehl(1.65um)=100%
Jitter=[114,119] mas
Noise=328 mas
Flux=37 ph/fr/pix
DMs min/max
CWFS APDs raw values
CWFS#1 (config=1)
20 13 11 19
Sum =63
Peak=20
CWFS#2 (config=1)
14 13 19 33
Sum =79
Peak=33
CWFS#3 (config=1)
228 262 273 243
Sum =1006
Peak=273
Slopes histogram
Slopes Histogram
number in bin
0 100 200 300
-2 -1 0 1 2
Slopes [arcsec]
RTD Controls
REPLAY MODE
x=4 y=1 (0) value=-3

# GeMS Operations

- Close the Laser loops and activate the 3 DMs
- Put NGS star on CR center, swap off-axis (f/32)
- Setup TTGS WFSs
- Canopus TTGS
  - Read out c3 and center it on star
  - Put c1 and c2 into astrometric mode and close loops
  - c1 and c2 are allowed to move independently to center on the guide stars (catalog inaccuracies)
  - The TTGS constellation defines the plate scale(!)
- GSAOI ODGWs haven't been tested yet

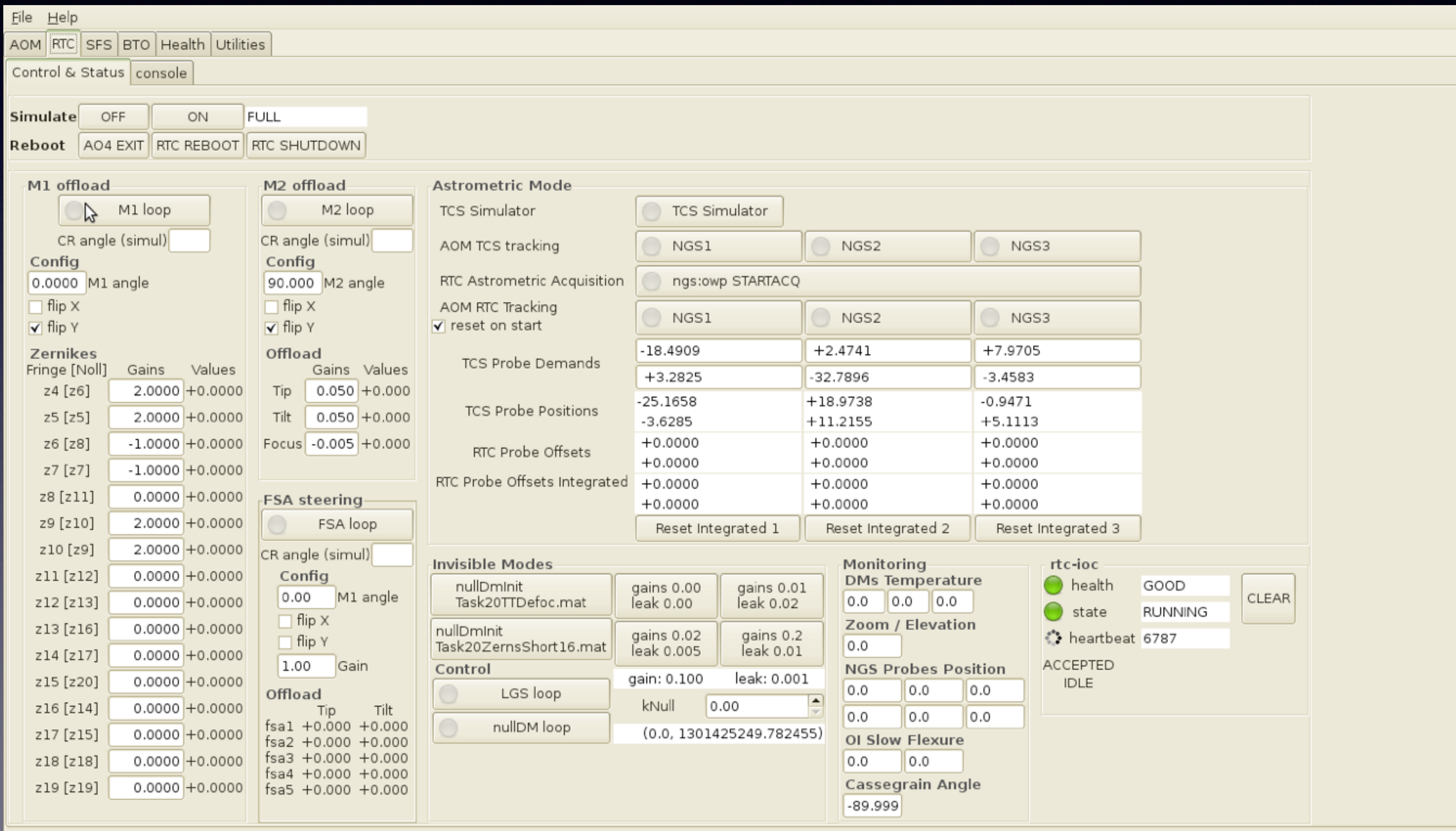
# GeMS Operations

- Myst spiral search tool makes finding stars much easier — start with c3



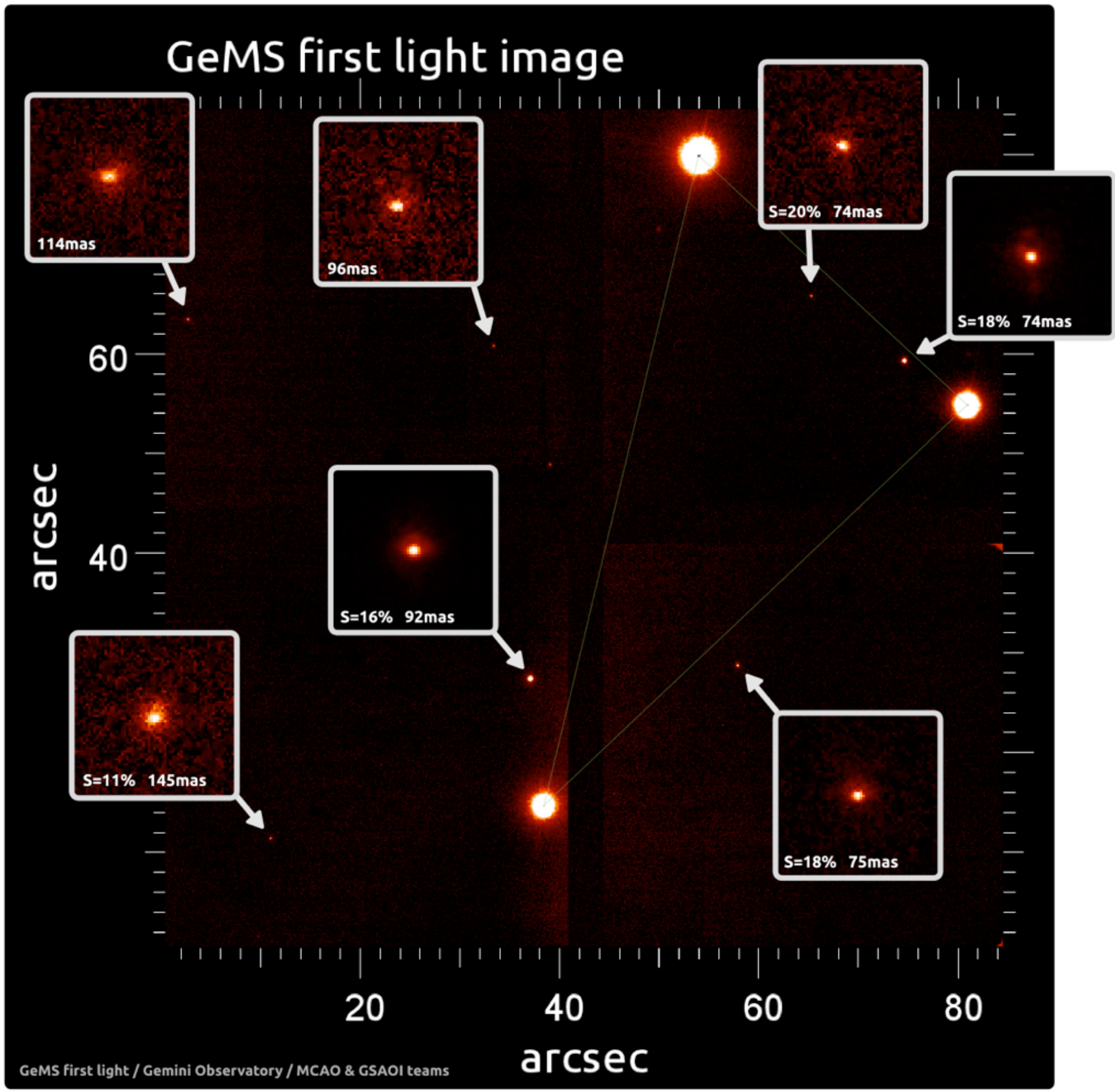
# GeMS Operations

- Now, put c1 and c2 into astrometric mode and find the guide stars



# GeMS Operations

- After this, close loops with SFS (nearly identical to the SFO), wait for it to converge and take data with the seqexec!



GeMS first light image
114mas
96mas
S=20% 74mas
S=18% 74mas
S=16% 92mas
S=11% 145mas
S=18% 75mas
60
40
arcsec
20
40
60
80
arcsec
GeMS first light / Gemini Observatory / MCAO & GSAOI teams

# GeMS Operations

- What do you do with GeMS?
- Photometry of any spatially resolved region bright in the IR
    - Galactic Center, Magellanic Clouds
    - Star Forming Regions
    - Shock Regions, Young Stellar Objects
    - Globular Clusters
    - Galaxy Clusters
    - Jupiter? Saturn?
- ACS WFC has a field of view of 202". GSAOI has a field of view of 85" and better angular resolution.